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Air Data System Calibration of F-16B S/N 92-0457
(Project TRUE PHOENIX)

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FINAL TECHNICAL INFORMATION MEMORANDUM

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AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

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14. ABSTRACT

This report presents the results of a limited air data system calibration on F-16B S/N 92-0457. The position error corrections, total pressure error, total air temperature probe recovery factor, and angle of attack effects were determined though flight test and are presented in this report. Testing began on 7 April and was completed on 30 April 2004 after eight missions.

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PREFACE

The test team owed special acknowledgement to Lt Col Michael Taschner for his pursuit of the perfect three-leaf cloverleaf and his mathematical genius in improving our brute force spreadsheet into an efficient data reduction tool. His efforts provided us with an independent verification and validation of our cloverleaf data reduction tools.

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EXECUTIVE SUMMARY

This report presents the objectives, procedures, and results of the TRUE PHOENIX test project. TRUE PHOENIX determined the Pitot-static position correction for "Coral Phoenix" F-16B, S/N 92-0457. These corrections will support the use of S/N 92-0457 as a high-speed pacer aircraft for the calibration of other aircraft air data systems and replace an older F-16B (S/N 80-0633). Ground testing of the Pitot-static system was conducted from 19 February to 5 April 2004, and flight testing was conducted from 7 April to 30 April 2004 with a total of eight missions.

The pacer instrumentation on F-16B S/N 92-0457 used the production F-16B noseboom-mounted air data probes to collect data for both total and static pressure systems. A total air temperature probe was mounted on the underside of the left forebody strake and provided the pacer air data computer with an air temperature measurement. The pacer instrumentation did not affect the performance or flying qualities of the aircraft.

The overall test objective was to determine the air data system position error corrections of F-16B S/N 92-0457. This objective was met and the position error corrections were determined using the tower fly-by and F-15B pace flight test techniques. Independent validation of these position error corrections were attempted using the level acceleration/deceleration and cloverleaf flight test techniques. In addition, a limited investigation into angle of attack effects was accomplished using the constant airspeed turn flight test technique.

Overall, while position error corrections were determined for calibrating F-16B S/N 92-0457, the reliability of the position error corrections at some altitudes were questionable and challenged the ability to use this aircraft as a high-speed pacer aircraft. According to theory, the Mach number position error correction data at all altitudes should collapse into a single curve and be similar to the previous pacer aircraft, F-16B S/N 80-0633. The difference in results from the various flight test techniques requires further investigation to explain the data scatter. Also, the total air temperature probe testing resulted in a recovery factor of 0.98, slightly below that expected from a flight test probe, and should be investigated for defects before use as a high-speed pacer aircraft.

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TABLE OF CONTENTS

Page No.

PREFACE ... **iii**

EXECUTIVE SUMMARY ... **v**

TABLE OF CONTENTS ... **vii**

LIST OF FIGURES AND ILLUSTRATIONS ... **viii**

LIST OF TABLES ... **ix**

INTRODUCTION ... **1**

- GENERAL ... 1
- BACKGROUND ... 1
- PROGRAM CHRONOLOGY ... 2
- TEST ITEM DESCRIPTION ... 2
- TEST OBJECTIVES ... 5

TEST AND EVALUATION ... **7**

- GENERAL ... 7
- TEST OBJECTIVES ... 7
- TEST PROCEDURES ... 7
- TEST RESULTS ... 9
  - Position Error Corrections ... 9
  - Total Air Temperature Probe Recovery Factor ... 14
  - Cloverleaf Flight Test Technique Analysis ... 14

CONCLUSIONS AND RECOMMENDATIONS ... **17**

REFERENCES ... **19**

APPENDIX A – GRAPHICAL ILLUSTRATIONS ... **21**

APPENDIX B – LESSONS LEARNED ... **87**

APPENDIX C – INSTRUMENTATION LIST ... **89**

APPENDIX D – END-TO-END GROUND TEST RESULTS ... **91**

APPENDIX E – RAW DATA ... **93**

LIST OF ABBREVIATIONS ... **101**

DISTRIBUTION LIST ... **103**

LIST OF FIGURES AND ILLUSTRATIONS

Figure No.	Title	Page No.
Figure 1.	F-16B Production ADS with Pacer Connections	4
Figure 2.	Cloverleaf (Overhead View)	8
Figure 3.	Altitude Position Error Correction (Tower Fly-By)	23
Figure 4.	Radar Altimeter Output vs. Tower Flyby Grid Reading	24
Figure 5.	Altitude Position Error Correction (10,000 ft PA Pace)	25
Figure 6.	Altitude Position Error Correction (20,000 ft PA Pace)	26
Figure 7.	Altitude Position Error Correction (30,000 ft PA Pace)	27
Figure 8.	Altitude Position Error Correction (35,000 ft PA Pace)	28
Figure 9.	Altitude Position Error Correction (40,000 ft PA Pace)	29
Figure 10.	Altitude Position Error Correction (Tower Fly-By & Pace)	30
Figure 11.	Altitude Position Error Correction (Tower Fly-By and Extrapolatiion)	31
Figure 12.	Altitude Position Error Correction (10,000 ft PA Cloverleaf)	32
Figure 13.	Altitude Position Error Correction (20,000 ft PA Cloverleaf)	33
Figure 14.	Altitude Position Error Correction (30,000 ft PA Cloverleaf)	34
Figure 15.	Altitude Position Error Correction (35,000 ft PA Cloverleaf)	35
Figure 16.	Altitude Position Error Correction (10,000 ft PA Level Accel/Decel)	36
Figure 17.	Altitude Position Error Correction (20,000 ft PA Level Accel/Decel)	37
Figure 18.	Altitude Position Error Correction (30,000 ft PA Level Accel/Decel)	38
Figure 19.	Altitude Position Error Correction (35,000 ft PA Level Accel/Decel)	39
Figure 20.	Altitude Position Error Correction (40,000 ft PA Level Accel/Decel)	40
Figure 21.	Engine Airflow Effects (10,000 ft PA Level Accel/Decel)	41
Figure 22.	Altitude Position Error Correction (10,000 ft PA Constant Airspeed Turn)	42
Figure 23.	Zero Total Pressure Validation	43
Figure 24.	Airspeed Position Error Correction (Tower Fly-By)	44
Figure 25.	Airspeed Position Error Correction (10,000 ft PA Pace)	45
Figure 26.	Airspeed Position Error Correction (20,000 ft PA Pace)	46
Figure 27.	Airspeed Position Error Correction (30,000 ft PA Pace)	47
Figure 28.	Airspeed Position Error Correction (35,000 ft PA Pace)	48
Figure 29.	Airspeed Position Error Correction (40,000 ft PA Pace)	49
Figure 30.	Airspeed Position Error Correction (Tower Fly-By & Pace)	50
Figure 31.	Airspeed Position Error Correction (Tower Fly-By and Extrapolated)	51
Figure 32.	Airspeed Position Error Correction (10,000 ft PA Cloverleaf)	52
Figure 33.	Airspeed Position Error Correction (20,000 ft PA Cloverleaf)	53
Figure 34.	Airspeed Position Error Correction (30,000 ft PA Cloverleaf)	54
Figure 35.	Airspeed Position Error Correction (35,000 ft PA Cloverleaf)	55
Figure 36.	Airspeed Position Error Correction (10,000 ft PA Level Accel/Decel)	56
Figure 37.	Airspeed Position Error Correction (20,000 ft PA Level Accel/Decel)	57
Figure 38.	Airspeed Position Error Correction (30,000 ft PA Level Accel/Decel)	58
Figure 39.	Airspeed Position Error Correction (35,000 ft PA Level Accel/Decel)	59
Figure 40.	Airspeed Position Error Correction (40,000 ft PA Level Accel/Decel)	60
Figure 41.	Mach Number Position Error Correction (Tower Fly-By)	61
Figure 42.	Mach Number Position Error Correction (10,000 ft PA Pace)	62
Figure 43.	Mach Number Position Error Correction (20,000 ft PA Pace)	63
Figure 44.	Mach Number Position Error Correction (30,000 ft PA Pace)	64
Figure 45.	Mach Number Position Error Correction (35,000 ft PA Pace)	65
Figure 46.	Mach Number Position Error Correction (40,000 ft PA Pace)	66
Figure 47.	Mach Number Position Error Correction (Tower Fly-By & Pace)	67
Figure 48.	Mach Number Position Error Correction (10,000 ft PA Cloverleaf)	68
Figure 49.	Mach Number Position Error Correction (20,000 ft PA Cloverleaf)	69
Figure 50.	Mach Number Position Error Correction (30,000 ft PA Cloverleaf)	70

Figure 51. Mach Number Position Error Correction (35,000 ft PA Cloverleaf)....71
Figure 52. Mach Number Position Error Correction (10,000 ft PA Level Accel/Decel)....72
Figure 53. Mach Number Position Error Correction (20,000 ft PA Level Accel/Decel)....73
Figure 54. Mach Number Position Error Correction (30,000 ft PA Level Accel/Decel)....74
Figure 55. Mach Number Position Error Correction (35,000 ft PA Level Accel/Decel)....75
Figure 56. Mach Number Position Error Correction (40,000 ft PA Level Accel/Decel)....76
Figure 57. Mach Number Position Error Correction (10,000 ft Constant Airspeed Turn)....77
Figure 58. Position Error Pressure Coefficient Angle of Attack Effects....78
Figure 59. Altitude Position Error Correction Angle of Attack Effects....79
Figure 60. Mach Number Position Error Correction Angle of Attack Effects....80
Figure 61. Total Air Temperature Probe Recovery Factor (Tower Fly-By & Pace)....81
Figure 62. Total Air Temperature Probe Recovery Factor (10,000 ft PA Level Accel/Decel)....82
Figure 63. Total Air Temperature Probe Recovery Factor (20,000 ft PA Level Accel/Decel)....83
Figure 64. Total Air Temperature Probe Recovery Factor (30,000 ft PA Level Accel/Decel)....84
Figure 65. Total Air Temperature Probe Recovery Factor (35,000 ft PA Level Accel/Decel)....85
Figure 66. Total Air Temperature Probe Recovery Factor (40,000 ft PA Level Accel/Decel)....86
Figure 67. Rear Cockpit Pacer Controls And Time Display....87
Figure 68. Rear Cockpit Data Display....88

LIST OF TABLES

Table No. Title Page No.

Table 1. Test Mission Chronology....2
Table 2. Total Air Temperature Probe Calibration Summary....14
Table 3. Cloverleaf Wind Analysis....15
Table 4. Cloverleaf Inter-leg Wind Analysis....16
Table 5. End-to-End Ground Test Results....91
Table 6. Tower Fly-by Aircraft Raw Data....93
Table 7. Fly-By Tower Raw Data (7 April 2004)....95
Table 8. Fly-By Tower Raw Data (12 April 2004)....96
Table 9. Fly-By Tower Raw Data (13 April 2004)....97
Table 10. Fly-By Tower Raw Data (30 April 2004)....98
Table 11. Pace Raw Data....99

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INTRODUCTION

GENERAL

The TRUE PHOENIX project determined the Pitot-static position corrections for "Coral Phoenix"[1] F-16B, S/N 92-0457. These corrections will support the use of S/N 92-0457 as a high-speed pacer aircraft for the calibration of other aircraft air data systems and to replace an older F-16B (S/N 80-0633). The aircraft used the production Pitot-static probe to feed sensitive pressure transducers and the production air data computer. Temperature data were collected and recorded to determine the total air temperature probe recovery factor. The corrected airspeed and altitude results were displayed in the cockpit and recorded by a digital data acquisition system for additional analysis.

This project established the static source position error corrections for the Pitot-static systems on F-16B S/N 92-0457 and calibrated the total air temperature probe. Several flight test techniques (FTTs) were used to support data collection to include: tower fly-by, pace with the Air Force Flight Test Center (AFFTC) F-15B pacer, and GPS techniques including the cloverleaf, level acceleration/deceleration and constant airspeed turn FTTs.

Flight testing was performed at the AFFTC in April 2004 by the TRUE PHOENIX test team. Eight F-16B test missions were successfully accomplished to support the test program, one of which was a two-ship mission with an F-15B (S/N 76-0132) for the pace flight. An Advanced Range Data System (ARDS) pod was carried on missions requiring precise GPS position and velocity.

BACKGROUND

Two AFFTC pacer aircraft, F-15B S/N 76-0132 and F-16B S/N 80-0633, had previously been used by the flight test center with re-calibrations twice per year. In 2004, F-16B S/N 80-0633 was replaced with a "Coral Phoenix" F-16B, S/N 92-0457, as the new AFFTC F-16B pacer aircraft.

Historically, pacer aircraft were used in the speed range from 200 KCAS to 0.93 Mach number and from the surface to 50,000 feet pressure altitude. The 0.93 Mach number "limit" was based on the shape of the Pitot-static position error correction curves. The F-15B pacer traditionally used the same "limit" solely because a higher Mach number requirement had not been identified by a customer. The TRUE PHOENIX test team conducted testing from approach speed (11 degrees angle of attack) to 1.4 Mach number.

[1] The name "Coral Phoenix" designates a group of F-16s originally built for Pakistan, but never delivered. These aircraft were then retrofitted for use at the Air Force test centers in a test support role.

PROGRAM CHRONOLOGY

The flight test missions were accomplished on the following dates:

Date	Flight Test Technique(s)	Mission Duration (hours)	Notes
7 April 04	Tower Fly-By	1.5	
12 April 04	Tower Fly-By	1.5	
13 April 04	Tower Fly-By	1.5	
14 April 04	Pace	1.7	
16 April 04	Cloverleaf	1.9	
20 April 04	Cloverleaf, Level Acceleration/Deceleration	1.4	
23 April 04	Level Acceleration/Deceleration, Constant Airspeed Turn	1.5	
30 April 04	Tower Fly-By, Level Acceleration/Deceleration, Cloverleaf	1.3	Heads-Up Display failure

Table 1. Test Mission Chronology

TEST ITEM DESCRIPTION

F-16B Pacer Air Data System

A schematic of the production F-16B air data system is illustrated in Figure 1. This figure has been modified to depict where the pacer sensitive pressure transducers were connected. The production air data system included a Pitot-static probe mounted on the nose that provided a dual source of static and total pressures. A second air data probe was mounted on the forward right side of the fuselage, which provided another source of static and total pressures for a production Pitot-static system. A total air temperature probe was mounted on the underside of the left forebody strake and provided the pacer air data computer with an air temperature measurement.

The pacer instrumentation on F-16B S/N 92-0457 used the production F-16B noseboom-mounted air data probes to collect data for both total and static pressure systems. The air data probe incorporated two separate static and Pitot ports comprising two Pitot-static systems. Each of the Pitot-static systems was connected to calibrated pressure transducers. The sensitive transducers provided input signals to the Advanced Airborne Test Instrumentation System (AATIS) which outputted engineering unit data to the pacer cockpit displays, a PC-104 flashcard memory, and a Mars II digital recorder.

The pacer cockpit displayed calibrated data (data corrected for both instrument and position errors) in a digital format. Both the Pitot-static system source presented on the display screens and the pacer system data recording rate were selectable from the rear cockpit. The

PC-104 was the primary pacer data recording system and recorded calibrated data from both Pitot-static systems for post-flight analysis. The Mars II tape recorder was used to record the AATIS pulse code modulation (PCM) data, voice, time code, and 1553 avionics multiplexer bus data for post flight analysis. The AATIS PCM stream included instrument-corrected static and total pressure, as well as total air temperature from both Pitot-static systems. Major AATIS components included the following:

1) MARS II digital recorder: recorded all AATIS instrumentation parameters, to include pacer system control unit (SCU)-3 outputs and 1553 avionics MUX bus data.

2) PS-7000 Sonix pressure transducers: converted total and static pneumatic pressures to digital format for AATIS.

3) PC-104 computer: configured and programmed for serial input, digital input, digital output, and PCMCIA flashcard recording capability. This computer was a commercial-off-the-shelf IBM computer for industrial embedded applications.

4) GPS time code generator: provided automatic synchronization with GPS satellites to generate the IRIG-B Time Code.

Further information on the pacer air data system was presented in the F-16B S/N 92-0457 Modification Flight Manual, Reference 1.

Air Data System Schematic (Typical)

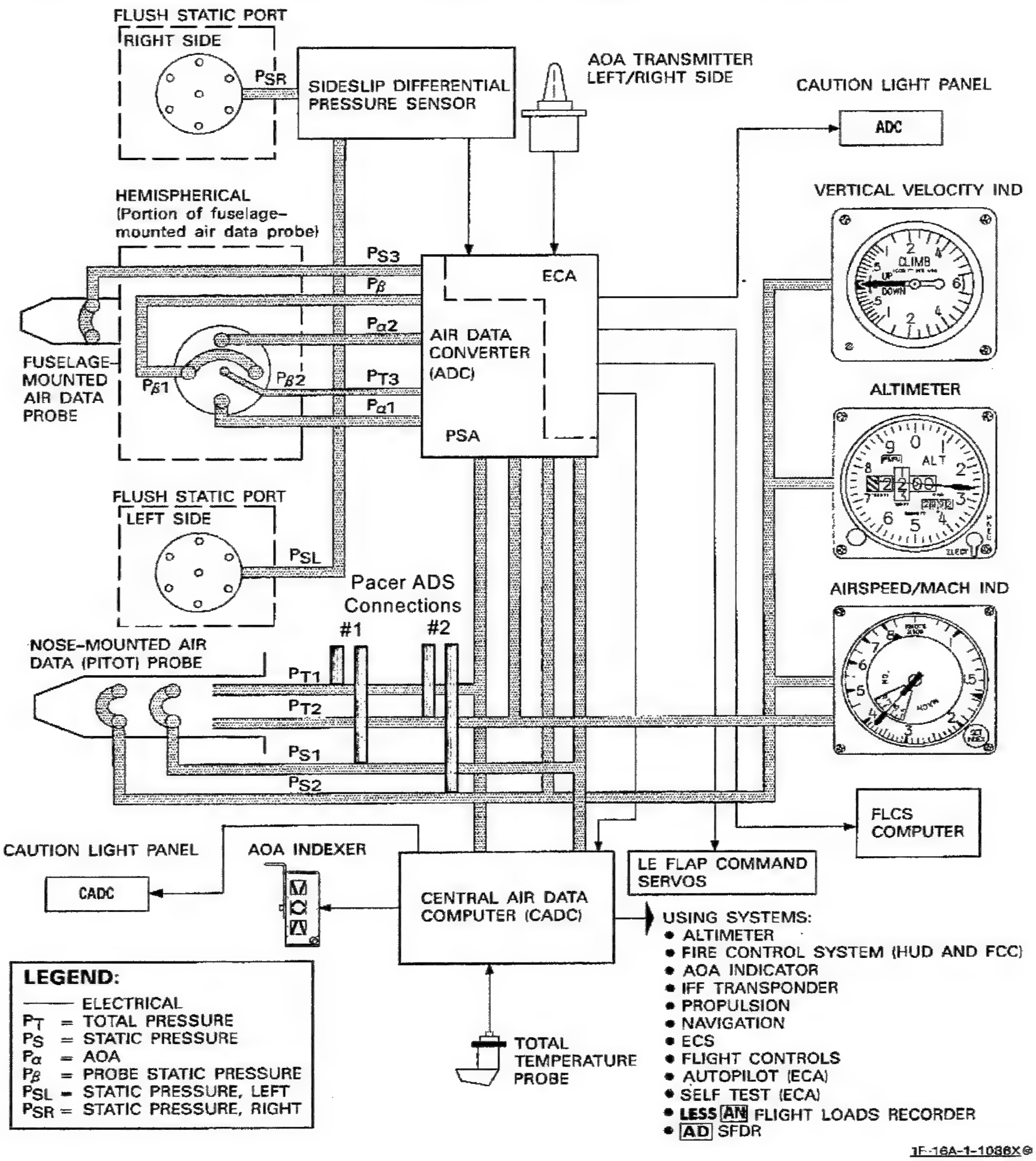

Figure 1. F-16B Production ADS with Pacer Connections

Test Aircraft

The F-16B was a two-seat fighter aircraft which also served in a training role. The fuselage was characterized by a large bubble canopy, forebody strakes, and an under fuselage engine air inlet. The aircraft was powered by a single F100-PW-220 afterburning turbofan

engine with a maximum thrust of approximately 25,000 pounds. For a complete description of the F-16B, refer to the F-16B Flight Manual and the F-16B Supplemental Flight Manual, References 2 and 3.

The test aircraft was flown with two external tanks on the wings and an Advanced Range Data System (ARDS) pod on a wingtip station (when required). A single ARDS pod on the wingtip was assumed to have negligible affects on the aircraft's Pitot-static system.

TEST OBJECTIVES

The overall test objective was to determine the air data system position error corrections of F-16B, S/N 92-0457. In order to accomplish this objective, a series of specific objectives were identified:

- Determine the air data system calibration using the tower fly-by technique
- Determine the air data system calibration using the pace technique
- Determine the effect of angle of attack on the position error corrections
- Compare the air data system calibration using the cloverleaf flight test technique to the air data system calibration using the tower fly-by and pace techniques
- Compare the air data system calibration using the level acceleration and deceleration flight test techniques to the air data system calibration using the tower fly-by and pace techniques

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TEST AND EVALUATION

GENERAL

This report presents the procedures and detailed analysis of the test results for the TRUE PHOENIX test project. TRUE PHOENIX calibrated an F-16B, S/N 92-0457, to serve as a pacer aircraft for the calibration of other aircraft air data systems.

TEST OBJECTIVES

The overall test objective was to determine the air data system position error corrections of F-16B, S/N 92-0457. In order to accomplish this objective, a series of specific objectives were identified:

- Determine the air data system calibration using the tower fly-by technique
- Determine the air data system calibration using the pace technique
- Determine the effect of angle of attack on the position error corrections
- Compare the air data system calibration using the cloverleaf flight test technique to the air data system calibration using the tower fly-by and pace techniques
- Compare the air data system calibration using the level acceleration and deceleration flight test techniques to the air data system calibration using the tower fly-by and pace techniques

TEST PROCEDURES

Prior to flight test, a ground checkout occurred from 19 February to 5 April 2004. During this checkout, the pressure transducers for static and total pressure were calibrated in the calibration lab using standard laboratory procedures. Next, installed end-to-end system checks were performed, using a TTU-205 test set to generate pneumatic pressures (Appendix D). The purpose of this calibration was to verify the pacer system was operating correctly and did not have any leaks in the system. The leak check was performed at 400 KCAS and 20,000 feet pressure altitude, and had a leak rate tolerance of less than 1 KCAS per minute in airspeed and 100 feet per minute in pressure altitude. Near the end of flight testing (28 April 2004), another end-to-end system check and leak check were accomplished to verify that no changes in the Pitot-static system had occurred during flight testing.

The following procedures were used to accomplish each flight test technique (FTT):

1) **Tower fly-by** – this FTT was flown in accordance with AFFTCI 11-1, Reference 4. The aircraft flew past the fly-by tower on the fly-by line at a target height of 100 ± 50 feet above ground level (AGL) with a tolerance of less than 100 feet per minute vertical velocity. The target airspeed was established within 5 KCAS and maintained within ±2 KCAS as the aircraft

approached the tower. A build-up approach from mid-speed to high-speed and mid-speed to low-speed data points was followed. If all mid-speed data points had been accomplished, a minimum of one mid-speed point was practiced prior to any high- or low-speed data points.

2) **Pace** – this FTT was flown with the F-15B in the lead and the F-16B as the wingman. The F-15B set up near the test point ±500 feet and ±0.01 Mach number and called "stable" when stabilized within ±10 feet and ±2 KCAS relative to the target stable point. The wingman called for both aircraft to simultaneously record their data values when the F-16B was stable relative to the lead and approximately two F-15 wingspans (80-100 feet) line abreast. The F-15B then cleared the flight to the next calibration point after the data were collected. The calibration points were planned from 200 KCAS to 0.95 Mach number within each altitude.

3) **Constant airspeed turn** – this FTT was flown by first performing a wind calibration, maintaining a constant heading in level flight with no sideslip and no significant vertical velocity for ten seconds at the target altitude (±1000 feet) and at the target Mach number (±0.02M). Altitude and airspeed tolerances were ±100 feet and ±5 KCAS. Next, the aircraft was rolled into a level turn and the load factor was increased by 0.5g. Once stabilized at a constant airspeed/Mach number, the turn was continued for a full 360 degrees. These level turns were repeated with increasing load factor until the maximum constant airspeed load factor was reached using military power. A wind calibration was repeated at least every ten minutes while performing turns at a similar Mach number, and a final wind calibration was accomplished after the turn sequence was complete for a target Mach number. The target altitudes were planned from lowest to highest, and the target airspeeds were planned from highest to lowest.

4) **Cloverleaf** – this FTT was flown by accomplishing three passes through a point in the sky at the same pressure altitude and calibrated airspeed on three different courses approximately 120° apart (Figure 2). The actual courses were not critical in this technique, and the team chose to fly aircraft heading vice ground track. A data band of ±1000 feet and ±0.02 Mach number with a data tolerance of ±100 feet and ±2 KCAS were used emphasizing the need to be stable on airspeed and altitude for each pass. An Advanced Range Data System (ARDS) pod was carried to determine accurate ground speed and ground track. Crew judgment determined when a stable ground speed and ground track were achieved. Further information about this FTT is presented in the Cloverleaf Flight Test Technique Analysis section.

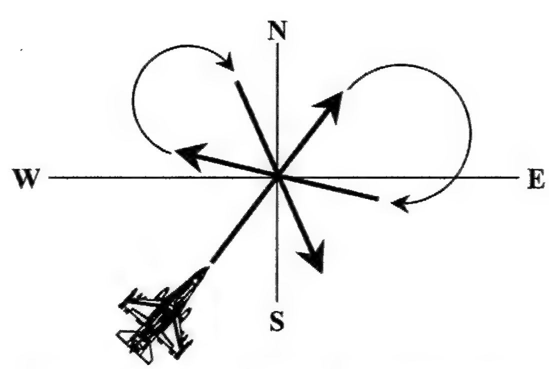

Figure 2. Cloverleaf (Overhead View)

5) **Level acceleration/deceleration** – this FTT was flown within the Black Mountain Supersonic Corridor, with the first pass consisting of a slow acceleration from approach speed or a performance-defined minimum airspeed through 1.4 Mach number or 580 KCAS (whichever was lower) at a rate of 5 KCAS per second. This was immediately followed by a deceleration from 1.4 Mach number or 580 KCAS (whichever was lower) to approach speed at a rate of 5 KCAS per second. Next, the aircraft flew the same course at the same altitude in the opposite direction at a constant airspeed (300 KIAS or 250 KIAS). The tapeline altitudes obtained from the GPS ARDS pod were used to calibrate the air data system. This method assumed that the aircraft was successfully calibrated at the chosen steady airspeed using the tower flyby and pace methods.

TEST RESULTS

The overall test objective was to determine the air data system position error corrections of F-16B S/N 92-0457. This objective was met and the position error corrections were determined using the tower fly-by and F-15B pace flight test techniques. Independent validation of these position error corrections were attempted using the level acceleration/deceleration and cloverleaf flight test techniques. In addition, a limited investigation into angle of attack effects was accomplished using the constant airspeed turn flight test technique.

Overall, while position error corrections were determined for calibrating F-16B S/N 92-0457, the reliability of the position error corrections at some altitudes were questionable and challenged the ability to use this aircraft as a high-speed pacer aircraft. According to theory, the Mach number position error correction data at all altitudes should collapse into a single curve and be similar to the previous pacer aircraft, F-16B S/N 80-0633. The difference in results from the various flight test techniques requires further investigation to explain the data scatter. Also, the total air temperature probe testing resulted in a recovery factor of 0.98, slightly below that expected from a flight test probe, and should be investigated for defects before use as a high-speed pacer aircraft.

Throughout this section, all figures that are referenced are located in Appendix A. All altitudes referenced throughout this section are pressure altitude unless otherwise noted.

Position Error Corrections

The primary objective of this project was to determine the position error corrections of F-16B, S/N 92-0457, throughout the range of altitudes from tower fly-by altitude (approximately 2300 feet pressure altitude) to 40,000 feet pressure altitude and from approach speed (11 degrees angle of attack) to 1.4 Mach number. The tower fly-by and pace FTTs were used to determine the curves between 200 KCAS and 0.93 Mach number at these altitudes. The cloverleaf, level acceleration/deceleration, and constant airspeed turn FTTs were used to independently validate these position error corrections. In addition, the constant airspeed turn FTT was used to determine the effect of angle of attack on the position error corrections.

Altitude Position Error Correction

Tower Fly-By

The results from the four tower fly-by flights formed a tightly-fit calibration curve with a maximum deviation of ±6 feet from the best-fit curve (Figure 3). Figure 4 displays the readings made by the tower observer versus the aircraft's radar altimeter output, with the actual grid reading versus altitude above ground level plotted as a theoretical curve. The radar altimeter output data vs grid reading were approximately ±5 to 6 feet relative to a line offset 3 to 4 feet below the theoretical relationship. This offset was due to the grid reading technique used and Figure 4 clearly illustrated that the tower observer correctly obtained the aircraft altitude, with a small error, as the aircraft passed the tower.

Pace

The altitude position error correction, ΔH_{pc}, formed a set of curves at different altitudes ranging from 10,000 feet to 40,000 feet. The data collected from the pace mission were used to develop a model at each altitude that was compared to the extrapolated tower fly-by curves (Figure 5 through Figure 9). These curves were also compared to the cloverleaf, constant airspeed turn, and level acceleration/deceleration FTT results. Since the tower fly-by data were the best data collected over the entire speed range, the Mach number position error correction curve data were converted to altitude position error corrections and extrapolated up to each altitude (Figure 11). The curves were created using Herrington's Flight Test Engineering Handbook (Reference 7). Overall, this extrapolation matched the pace model position and shape at low altitudes; however, as altitude increased the extrapolation fell further from the pace model. The family of extrapolated tower flyby curves were, in general, within approximately 50 feet of the pace data. Since this extrapolation was a data standardization technique, it was only used as a verification for each pace model at each altitude.

The data collected at 10,000 feet (Figure 5) fit the model curve well, with the exception of the 0.49 Mach number data point. This data point was the first data point collected during the mission, and the F-15 aircrew noted that the test aircraft was at a higher altitude than the pacer jet. Disregarding this point, the maximum deviation from the pace model was 15 feet at 0.54 Mach number. However, the data at the high-speed end of this curve appeared to be erroneous for a number of reasons. First, Figure 10 demonstrates that the curve crossed the 20,000 feet and 30,000 feet position error lines, resulting in a final transonic swing that does not coincide with the set of curves. Second, Figure 12, Figure 16, and Figure 22 demonstrate that the cloverleaf, level acceleration/deceleration, and constant airspeed turn FTTs produced a curve with a larger correction than the pace model. The tower fly-by extrapolation also supported this hypothesis since the high-speed portion of the curve had a larger correction than the pace model. These data indicated that the curve should remain above the 20,000 feet pace model and fit the set of curves.

The data at 20,000 feet (Figure 6) did not fit a curve well, with maximum deviations from the pace model of 34 feet at 0.45 Mach number and 0.69 Mach number. Reasons for the deviations at these data points are unknown. However, the level acceleration/deceleration data (Figure 17) and tower fly-by extrapolation support the general shape and position of the curve,

although the extrapolation was 10 to 15 feet above the curve. The data at 30,000 feet, 35,000 feet, and 40,000 feet (Figure 7, Figure 8, and Figure 9) all fit a curve well. The shape of each curve also matched that expected from an altitude position error correction curve based on the tower fly-by results. These best-fit curve models were plotted together in Figure 10.

Cloverleaf

The data from the cloverleaf FTT exhibited larger data scatter than the tower fly-by, pace, and acceleration/deceleration data. Figure 12 through Figure 15 compared the collected data with the best-fit model created from the pace data at each test altitude. Significant scatter around this best-fit model was most likely attributed to an invalid constant wind assumption and angle of attack instability. With the exception of the data points at 10,000 feet, the altitude calculated by applying the cloverleaf altitude position error correction was within 0.5 percent of the altitude predicted by the pace model, which in most applications would be acceptable. For example, a pacer aircraft at 40,000 feet using the cloverleaf model would be at most 200 feet different than a pacer aircraft at 40,000 feet using the pace model. The data at 10,000 feet were approximately ±50 feet of the extrapolated tower flyby data. In this case, the cloverlead data were not reliable enough to validate the data gathered from the pace FTT. Reference the Cloverleaf FTT Analysis in this section for conclusions and recommendations.

Level Acceleration/Deceleration

The level acceleration/deceleration flight test technique provided a better curve definition for determining whether the pace data were accurate due to the large number of data points gathered. Unfortunately, for this FTT to be accurate, the altitude position error correction was required at the airspeed used during the constant airspeed run. Multiple data points were taken at or near 300 KCAS at each altitude during the pace mission; however, at 10,000 feet and 20,000 feet these points were separated by 23 and 36 feet, respectively. For all altitudes, the best fit line through the pace data were used as the truth correction to apply to the constant airspeed pass. The resultant level acceleration/deceleration curves are displayed in Figure 16 through Figure 20. In all of the graphs, at some point (depending on altitude), the curves created with the level acceleration and the level deceleration split. This split, expanded in Figure 21, was most likely due to engine effects since the five knots per second acceleration was accomplished through a slow throttle movement, and the five knots per second deceleration was accomplished with the throttle at idle power. This difference in engine setting likely changed the pressure field near the nose of the aircraft which resulted in the shift in altitude position error correction. **Investigate the effects of engine airflow on Pitot-static position error corrections. (R1)**[2] Due to the fact that this aircraft will be used as a pacer with the throttle set at a position to maintain a constant airspeed, the acceleration data were primarily used when comparing to the pace results since it more accurately represented the engine airflow required during a typical pace mission.

Constant Airspeed Turns

The constant airspeed turn flight test technique provided a third comparison to validate the pace data. Since this technique was the test team's lowest priority, data were only collected at 10,000 feet. Figure 22 displays the results of this FTT compared against the pace model. As

[2] Numerals preceded by an R within parentheses correspond to the recommendation numbers in the Conclusions and Recommendations section of this report.

previously discussed, this constant airspeed turn data matched the level acceleration/deceleration and cloverleaf data, supporting the conclusion that the pace data at 10,000 feet above 0.6 Mach number were erroneous. Overall, the constant airspeed turn data quality collected was considered marginal due to gusty winds during the data collection. A more in-depth analysis is made in the Angle of Attack Effects section below.

Zero Total Pressure Error Analysis

When calculating the airspeed and Mach number position error corrections from the altitude position error corrections, the total pressure error present in the system was assumed to be zero. To determine whether this assumption was valid, the difference between the airspeed position error correction as calculated directly from the pacer and the airspeed position error when calculated from the altitude position error correction was determined. Figure 23 illustrates this difference (or "calibrated airspeed error") plotted versus instrument corrected Mach number. Typically, a zero total pressure error can be assumed when the data are centered on zero with scatter less than ±1 KCAS.

The majority of the data points in Figure 23 were centered on zero and were within ±3.3 knots of zero error. There were three points well outside of the data band. A data point at 0.57 Mach number and 30,000 feet as well as a data point at 0.68 Mach number and 40,000 feet were attributed to the two aircraft being at different airspeeds, thereby inducing error into the calculation and resulting in a calibrated airspeed error of greater than ±10 knots. A point at 0.94 Mach number and 10,000 feet also had a calibrated airspeed error of greater than 10 knots, but the cause of this large error could not be determined. This point was removed from the data analysis using engineering judgment. Only four other points had errors greater than ±3 KCAS. There were eight test points with errors between ±2 and 3 KCAS, and twenty test points with errors between ±1 and 2 KCAS. Only 29 of the 66 total test points had errors within ±1 KCAS. The cause of the larger-than-normal data scatter was not determined. In spite of the data scatter, the total pressure error was assumed to be zero.

Airspeed Position Error Correction

The airspeed position error correction, ΔV_{pc}, was determined from the tower fly-by altitude position error correction data (Figure 24) and from the pace altitude position error correction data (Figure 25 through Figure 29), assuming zero total pressure error. The results of those two flight test techniques are summarized in Figure 30. The tower fly-by results were extrapolated to higher altitudes and are presented in Figure 31.

The results from the cloverleaf flight test technique, an airspeed measurement technique, are presented in Figure 32 through Figure 35. The results from the level acceleration/deceleration flight test technique are presented in Figure 36 through Figure 40. The analysis, conclusions, and recommendations made in the altitude position error correction section directly apply to the airspeed position error correction data since the same data were used to derive these results.

Mach Number Position Error Correction

The Mach number position error correction, ΔM_{pc}, was determined from the tower fly-by altitude position error correction data (Figure 41) and from the pace altitude position error correction data (Figure 42 through Figure 46). The Mach number position error correction fairings are summarized in Figure 47. Mach number position error corrections were also determined from the cloverleaf FTT data (Figure 48 through Figure 51), from the level acceleration/deceleration data (Figure 52 through Figure 56), and from the constant airspeed turn data at 10,000 feet (Figure 57). Ideally, this data should fit a single curve, assuming that angle of attack effects are negligible. **Determine why Mach number position error corrections at all altitudes did not conform to theory. (R2)** As in the airspeed position error corrections, the analysis, conclusions, and recommendations made in the altitude position error correction section directly apply to the Mach number position error correction data since the same data were used to derive these results.

Angle of Attack Effects

In order to analyze angle of attack effects on the position error corrections, a series of constant airspeed turns were conducted with varying load factor. Unfortunately, one of the primary assumptions was that the winds at the target altitude were constant in magnitude and heading for the duration of the turn. During the mission when this maneuver was accomplished, the winds were extremely gusty, making it difficult for the aircraft to maintain a constant airspeed over an entire 360 degree turn. Thus, most of the data were removed from the analysis due to the resultant airspeeds being well outside of tolerances. The data that are presented had a sinusoidal variation of airspeed over the duration of the turn but were bounded near the tolerance of ±5 KCAS.

Figure 58 presents the position error pressure coefficient, $\Delta P_p/q_{cic}$, versus angle of attack for each data point along with a 10,000 foot pace data best-fit curve. All of the data presented from this flight test technique fell around a best-fit line indicating the position error pressure coefficient was dependent on the angle of attack changes due to changes in Mach number. When comparing points at a constant Mach number the data indicated an angle of attack effect existed. The 0.9M points had the strongest correlation between changes in angle of attack and changes in the position error pressure coefficient, while the 0.7M points demonstrated a minimal change in position error pressure coefficient as the angle of attack changed. In general, the constant Mach number position error pressure coefficients did not generally follow the pace best-fit line (changes due to Mach number) as the angle of attack varied. Therefore, an angle of attack effect existed in the position error pressure coefficient which was independent of the angle of attack effect caused by changing Mach number. The exact relationship between angle of attack and position error pressure coefficient was unknown due to the limited data and the turbulent conditions in which the data were collected. Figure 59 and Figure 60 show similar relationships between altitude position error corrections and Mach number position error corrections. Each of

these graphs indicated a relationship between Mach number and changes in angle of attack that affected the position error corrections; the strongest correlations was at 0.9M and the weakest correlation at 0.7M.

Total Air Temperature Probe Recovery Factor

The total air temperature probe recovery factor was determined using both the tower fly-by and pace FTTs, and validated using the level acceleration/deceleration FTT. The recovery factor was successfully determined, as all data fell within ±0.05 of the best fit line of the instrument corrected total air temperature parameter, $5(T_{ic}/T_a -1)$. For the tower fly-by data, the instrument corrected temperature on the aircraft was compared to the ambient air temperature measured in the fly-by tower. During the pace, the temperature was compared to the ambient air temperature determined by the F-15B pacer jet. For the level accelerations and decelerations, the temperature was compared to the ambient air temperature from the rawinsonde balloons (balloon launches were within one hour of the takeoff time and launched ~30nm from the test run area). The resultant recovery factor (from the tower fly-by data) was 0.98, which was lower than historical results (Figure 61). While enough data were collected to provide confidence to this result, the difference with historical results called the condition of the total air temperature probe into question. Additional recovery factors were calculated using the acceleration/deceleration data and weather balloon data. The temperature recovery factors were calculated using the subsonic deceleration portion of the data due to the lower rate of change in airspeed. These results are presented in Figure 62 through Figure 66 and Table 2. **Determine the physical condition of the total air temperature probe prior to future aircraft calibrations. (R3)**

Flight Test Technique	Pressure Altitude (1000 feet)	Calculated Recovery Factor (N/D)	Calculated Bias (N/D)
Tower Fly-By	2.3	0.9818	-0.0416
Acceleration/Deceleration	10	0.9811	-0.0402
Acceleration/Deceleration	20	0.9457	-0.0238
Acceleration/Deceleration	30	0.9998	-0.0284
Acceleration/Deceleration	35	1.0644	-0.0638
Acceleration/Deceleration	40	0.8602	0.0780

Table 2. Total Air Temperature Probe Calibration Summary

Cloverleaf Flight Test Technique Analysis

Flying proper cloverleaf patterns took practice to accomplish with any degree of accuracy. The higher altitude patterns were the most challenging due to higher winds and low specific excess power. To minimize possible wind changes and to accomplish as many data points as possible during the flight, a minimum time to fly a maneuver was computed and used. To standardize the maneuver and ensure minimum maneuver time, a turn radius chart consisting of planned load factor (2g or 3g), airspeed, and altitude was used to compute a no-wind fly-out distance from the cloverleaf center point. This provided a starting point to adjust fly-out distance

real-time based on the test day winds. The legs with strong headwinds on the outbound portion were the most challenging because, if the fly-out distance was misjudged, little time was available to stabilize on an airspeed before the center point was crossed. Because of the small airspeed tolerances, calibrated airspeeds were computed for each test point to provide a target airspeed. Using these procedures, data were gathered within the established data bands and tolerances, but the graphs yielded significant scatter with no definable fairing.

First, the quality of the cloverleaf data was examined to yield any possible causes for the scatter. The 0.85M test points at all altitudes were consistently above a normal fairing of the data. The 0.85M test points were re-flown after the second ground test of the Pitot-static system and, while the results were closer to expected values, they still were significantly above the expected fairing of the data. Since the cloverleaf data accuracy was better when using constant airspeeds between legs, data points were selected with a focus on matching calibrated airspeeds. Each leg's data points were within 1 knot of each other and within fourteen seconds of the cloverleaf center point to attempt to satisfy the constant wind assumption.

Additionally, the constant wind assumption was examined to yield any possible causes for the scatter. The cloverleaf FTT data reduction assumed steady state winds throughout each approximately four minute maneuver. This assumption was evaluated by comparing the wind calculations from the cloverleaf data reduction for the different test points at the same altitude. If the calculated winds were consistent across five test points spanning approximately 20 minutes, the constant wind assumption was considered to be reasonable. The results of this analysis are shown in Table 3 with the worst wind deviation in magnitude and heading displayed in the rightmost column. The 10,000 foot data points were flown on two separate days, 0.5M through 0.8M on 23 April 2004 and 0.85 through 0.9M on 16 April 2004.

Alt	0.50M hdg/kts	0.60M hdg/kts	0.70M hdg/kts	0.80M hdg/kts	0.85M hdg/kts	0.90M hdg/kts	Deviation hdg/kts
10K	230.7/14.3	199.1/17.7	215.4/20.2	230.6/25.8	37.6/25.4	34.1/30.6	31.5/8.1
20K	29.5/60.7	30.1/60.9	29.3/60.2	30.6/61.3	31.0/61.3	29.8/61.3	1.8/1.1
30K		42.0/85.5	45.8/84.6	44.4/82.3	45.0/86.3	44.5/86.1	3.8/4.0
35K		47.5/88.1	46.4/89.3	47.2/90.4	46.0/87.6	46.6/88.7	1.5/2.8

Table 3. Cloverleaf Wind Analysis

Based on Table 3, the winds changed from 1.1 at 20,000 ft to 8.1 knots at 10,000 ft. Wind changes can have a significant effect on the ground speed used in the data reduction. For example, a change in wind velocity of 4 knots translated to an associated Mach number change of 0.011M at 30,000 ft. The winds further changed between legs on each cloverleaf. Table 4 shows the wind speed and heading along with the greatest deviation between a set of three cloverleaf legs. The winds were quite variable with the greatest heading change of 18 degrees and the greatest speed change of 8 knots. A change of 8 knots at 35,000 ft equates to a Mach number change of 0.025M. These wind changes violated the constant wind assumption used in the cloverleaf FTT and caused scatter in the data at a 0.01M resolution. Overall, the constant wind assumption was not valid.

	Leg 1 hdg/kts	Leg 2 hdg/kts	Leg 3 hdg/kts	Deviation hdg/kts
10K, 0.5M	252.1/19.9	204.5/22.5	233.9/15.7	18.2/4.2
20K, 0.8M	57.3/12.2	64.7/16.9	59.3/13.9	7.4/4.7
30K, 0.8M	31.1/84.4	31.8/84.3	25.9/82.4	5.2/2.0
35K, 0.8M	33.9/88.5	34.5/92.5	32.5/84.2	2.0/8.3

Table 4. Cloverleaf Inter-leg Wind Analysis

Finally, another possible reason for the scatter was airspeed stability during the three legs of the cloverleaf maneuvers. While the target airspeed was attained within data tolerances during each leg, the length of time at the target airspeed varied between legs. Based on the data, the first leg of every maneuver was the most stable with airspeed stability lasting more than five seconds. For some legs, the target airspeed was only attained for a second of time while the aircraft decelerated or accelerated through the airspeed. This was common on legs where the aircraft exhibited poor specific excess power (higher altitude points) and when the inbound distance was shortened by tailwinds. This airspeed instability translated into angle of attack instability and, as discovered during this project, angle of attack appeared to introduce some error into the pressure measurements which adversely affected the data. During each cloverleaf leg, the aircraft should be stabilized on airspeed and altitude to remove possible angle of attack effects and improve data quality.

Based on the ΔM_{pc} vs. Mach number cloverleaf graphs (Figure 48 through Figure 51), the Mach number calculated by applying the cloverleaf Mach number position error correction was within 0.7 percent of the Mach number predicted by the pace model. For example, a pacer aircraft at 300 KIAS using the cloverleaf model would be at most 2 KIAS different than a pacer aircraft at 300 KIAS using the pace model. A cloverleaf flight test technique test on the previous AFFTC pacer F-16B also yielded results within 1 percent of the calibration curves calculated via other FTTs (Reference 6). Therefore, based on this error spread, the most realistic position correction resolution was 0.005M for ΔM_{pc}. For some aircraft Pitot-static systems where this degree of error is acceptable, the cloverleaf FTT is a recommended technique. If a higher degree of accuracy is necessary, the cloverleaf FTT is not recommended as an air data system calibration FTT.

CONCLUSIONS AND RECOMMENDATIONS

The overall test objective was to determine the air data system position error corrections of F-16B S/N 92-0457. This objective was met and the position error corrections were determined using the tower fly-by and F-15B pace flight test techniques. Independent validation of these position error corrections were attempted using the level acceleration/deceleration and cloverleaf flight test techniques. In addition, a limited investigation into angle of attack effects was accomplished using the constant airspeed turn flight test technique.

The pace position error correction model at 10,000 feet did not fit the set of curves formed by the data at 30,000 feet, 35,000 feet, and 40,000 feet. The curve at 10,000 feet crossed the 20,000 feet and 30,000 feet position error correction curves, resulting in a final transonic swing that did not coincide with the family of curves. Second, the cloverleaf, level acceleration/deceleration, and constant airspeed turn flight test techniques produced a curve above the 10,000 feet pace model. The data at 20,000 feet did not fit a curve well, with maximum deviations of 34 feet (ΔH_{pc}) at 0.45 Mach number and 0.69 Mach number. Reasons for the deviations at these data points are unknown.

The level acceleration/deceleration data showed a potential engine airflow effect on Pitot-static position error corrections. At some point (depending on altitude), the curves created from the level acceleration and the level deceleration data split. This split, expanded was most likely due to engine effects since the five knots per second acceleration was accomplished through a slow throttle movement forward, and the five knots per second deceleration was accomplished with the throttle at idle power. This might adversely effect position error corrections and introduce error in future calibrations.

R1: Investigate the effects of engine airflow on Pitot-static position error corrections. (pg. 11)

The Mach number position error correction, ΔM_{pc}, formed a set of curves at different altitudes. In a similar fashion to the airspeed position error correction, the Mach number position error correction was also derived from the altitude position error correction, assuming zero total pressure error in the Pitot-static system. Theory suggests that this data should fit a single curve, assuming that angle of attack effects were negligible.

R2: Determine why Mach number position error corrections at all altitudes did not conform to theory. (pg. 13)

The total air temperature probe recovery factor was evaluated using both the tower fly-by and pace FTTs. The resultant recovery factor was 0.98, which was lower than other historical results. The difference with historical results calls the condition of the total air temperature probe into question.

R3: Determine the physical condition of the total air temperature probe prior to future aircraft calibrations. (pg. 14)

The cloverleaf data showed an unacceptable data scatter around the position error correction set of curves. While the target airspeed was attained within data tolerances during each cloverleaf leg, the length of time at the target airspeed varied between legs. For some legs, the target airspeed was only attained for a second of time while the aircraft decelerated or accelerated through the airspeed. This airspeed instability translated into angle of attack instability and, as discovered during this project, angle of attack appeared to introduce some error into the pressure measurements. During each cloverleaf leg, the aircraft should be stabilized on airspeed and altitude to remove possible angle of attack effects and improve data quality.

Based on the ΔM_{pc} vs. Mach number cloverleaf graphs, the cloverleaf data were within 1.2 percent of the position correction error from the data gathered from the other flight test techniques. A cloverleaf flight test technique test on the previous AFFTC pacer F-16B also yielded results within 1 percent of the calibration curves calculated via other flight test techniques. For some aircraft Pitot-static systems where this degree of error is acceptable, the cloverleaf FTT is a recommended technique.

Overall, while position error corrections were determined for calibrating F-16B S/N 92-0457, the reliability of the position error corrections at some altitudes were questionable and challenged the ability to use this aircraft as a high-speed pacer aircraft. According to theory, the Mach number position error correction data at all altitudes should collapse into a single curve and be similar to the previous pacer aircraft, F-16B S/N 80-0633. The difference in results from the various flight test techniques requires further investigation to explain the data scatter. Also, the total air temperature probe testing resulted in a recovery factor of 0.98, slightly below that expected from a flight test probe, and should be investigated for defects before use as a high-speed pacer aircraft.

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APPENDIX A – GRAPHICAL ILLUSTRATIONS

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Figure 3. Altitude Position Error Correction (Tower Fly-By)

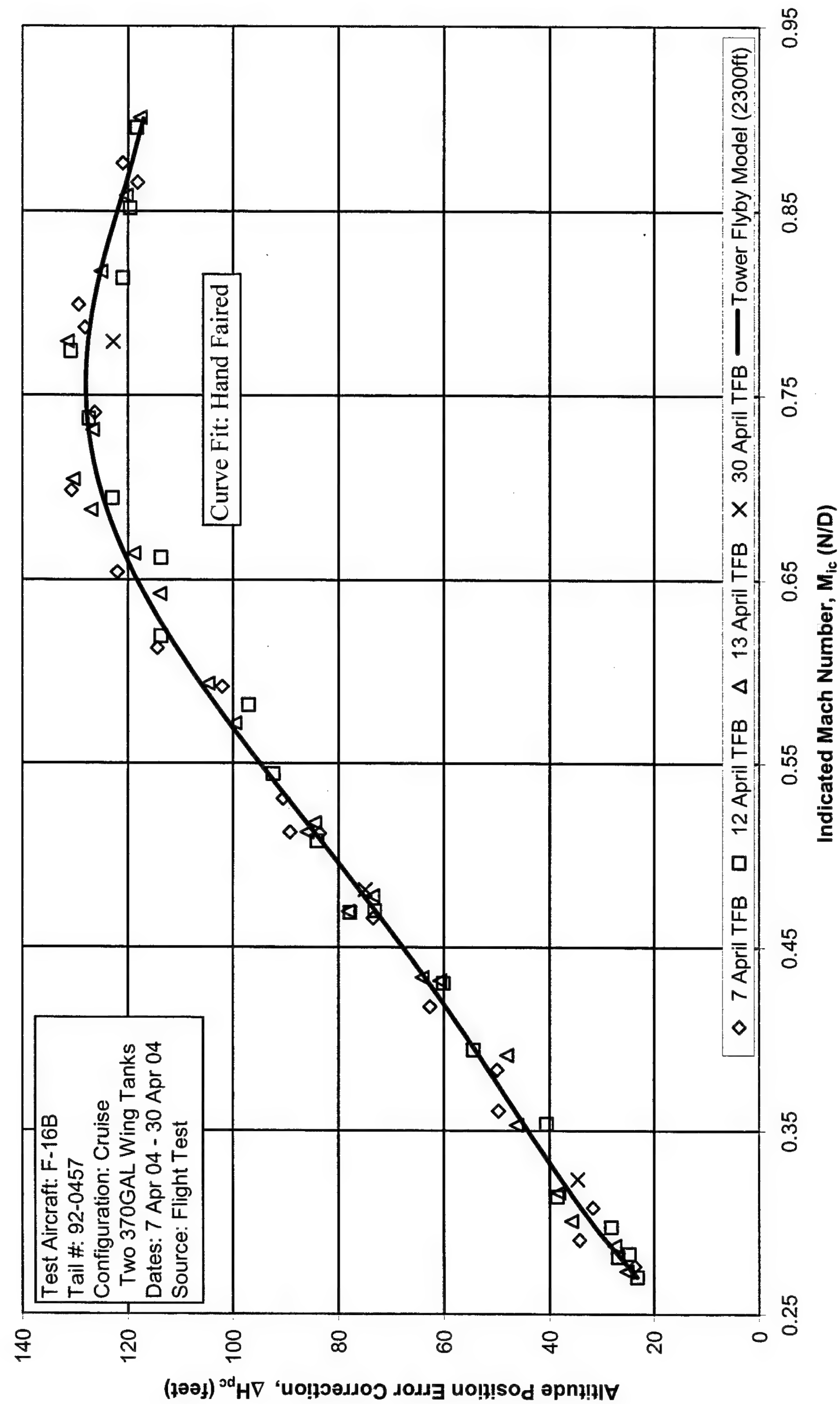
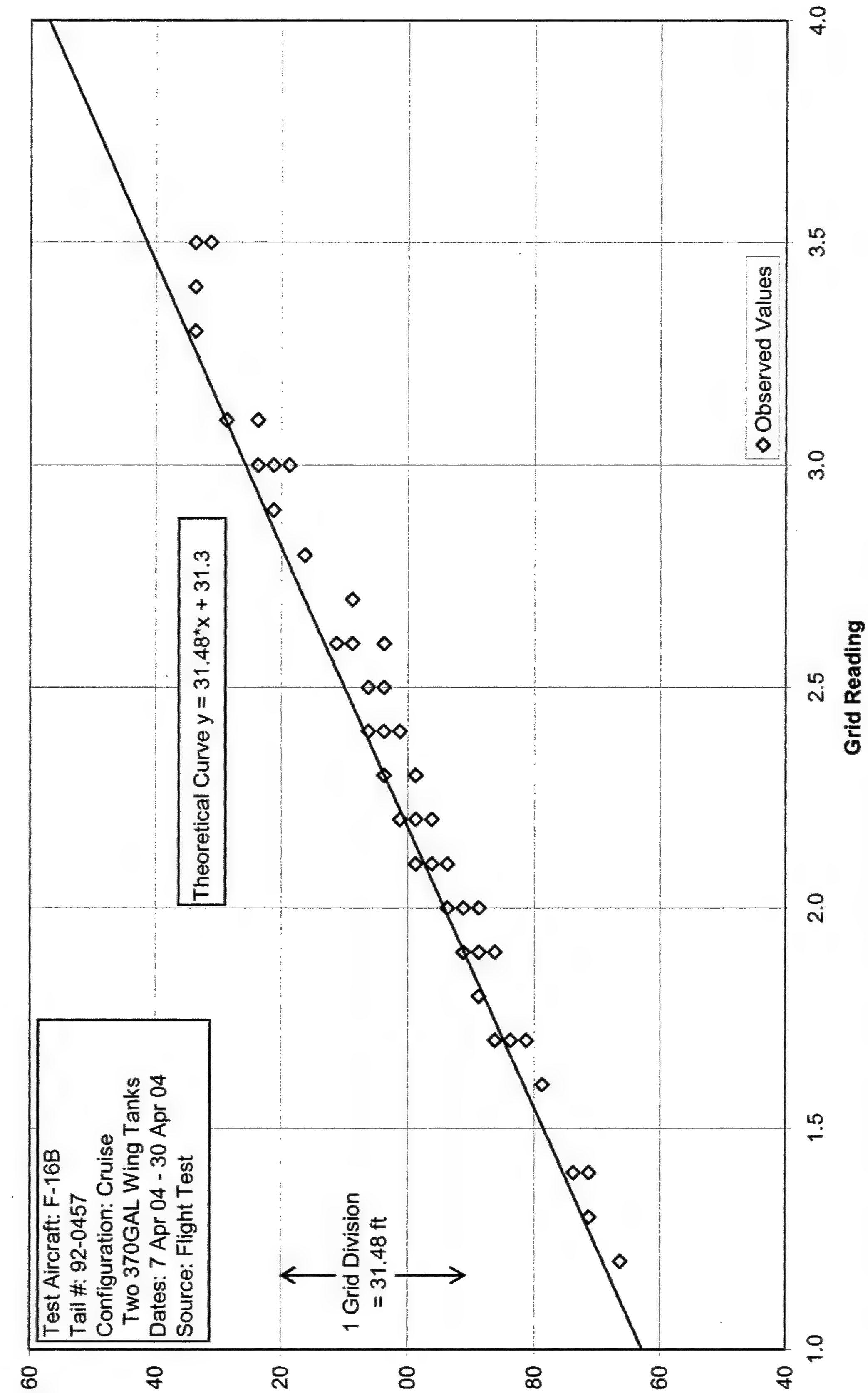


Figure 4. Radar Altimeter Output vs. Tower Flyby Grid Reading



Note: Theoretical Curve based on survey data corrected for radar altimeter antenna location

Figure 5. Altitude Position Error Correction (10,000 ft PA Pace)

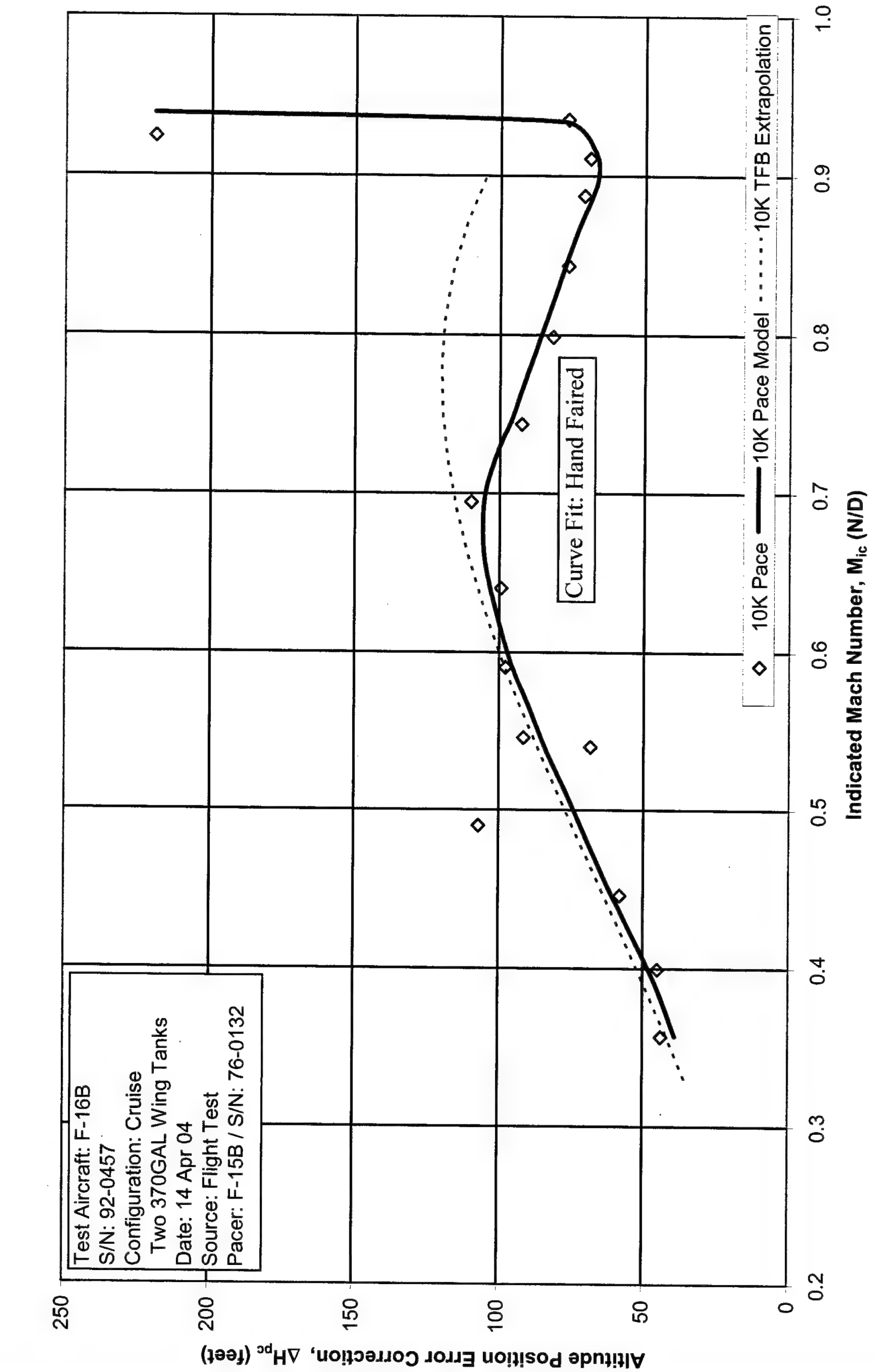


Figure 6. Altitude Position Error Correction (20,000 ft PA Pace)

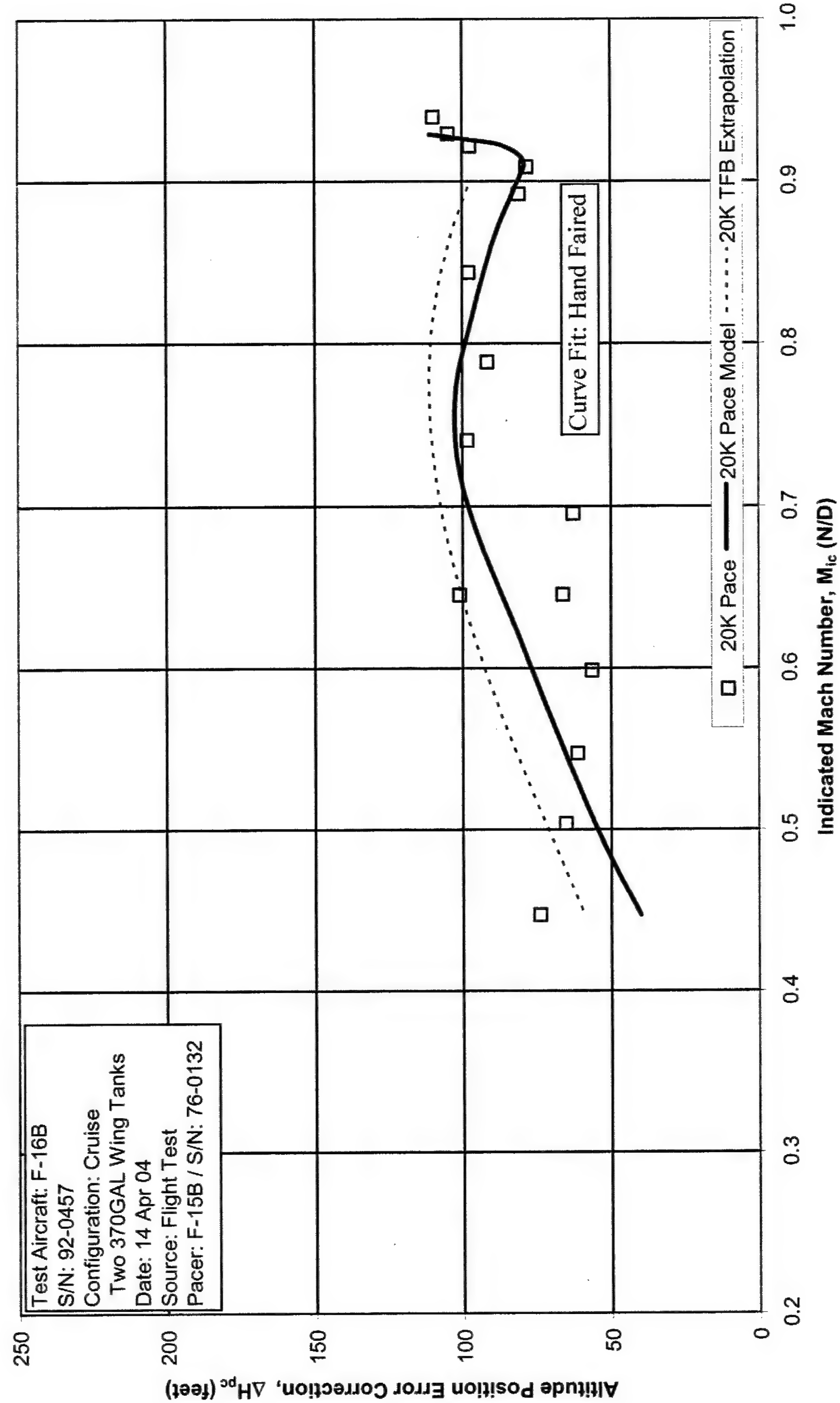


Figure 7. Altitude Position Error Correction (30,000 ft PA Pace)

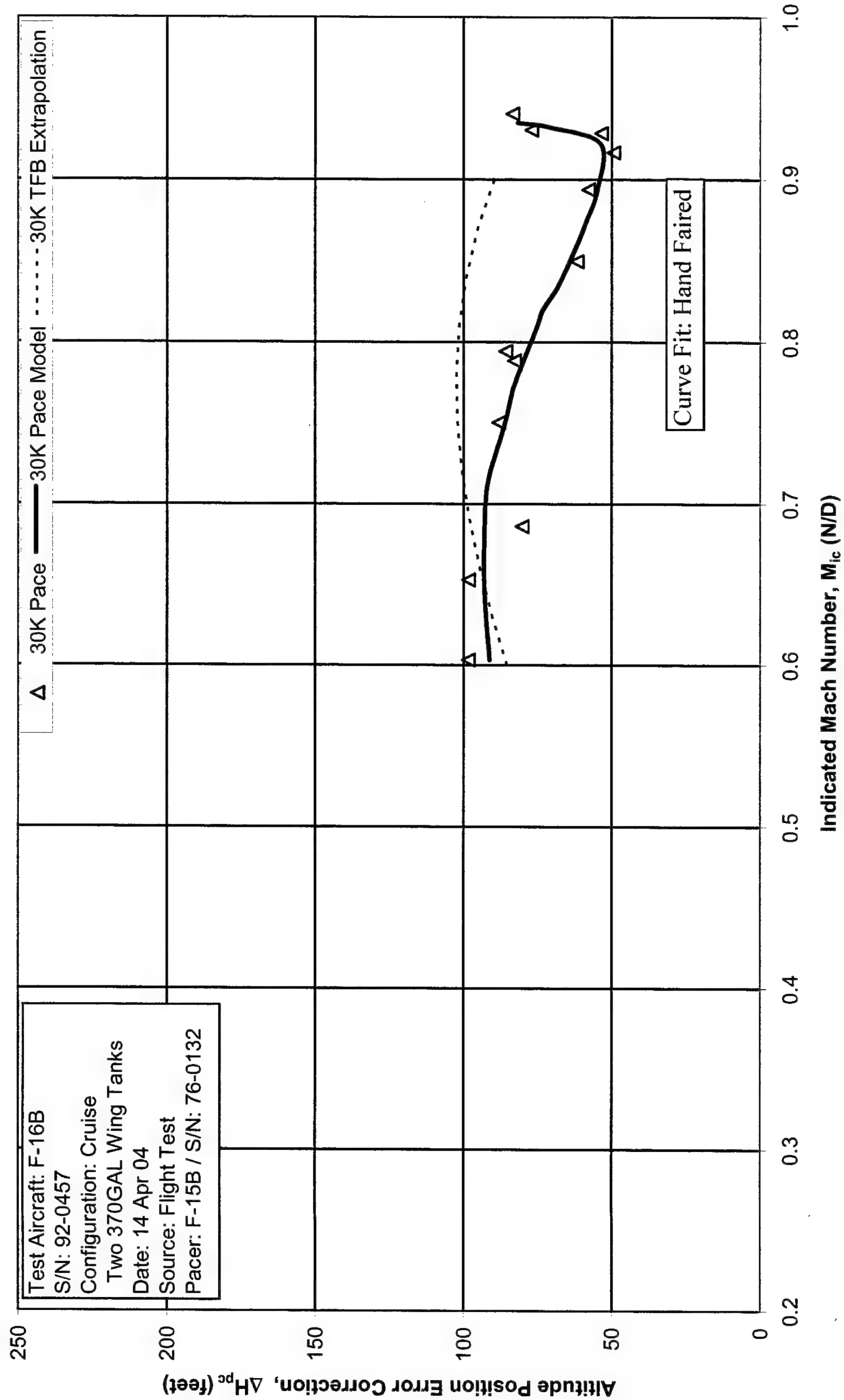


Figure 8. Altitude Position Error Correction (35,000 ft PA Pace)

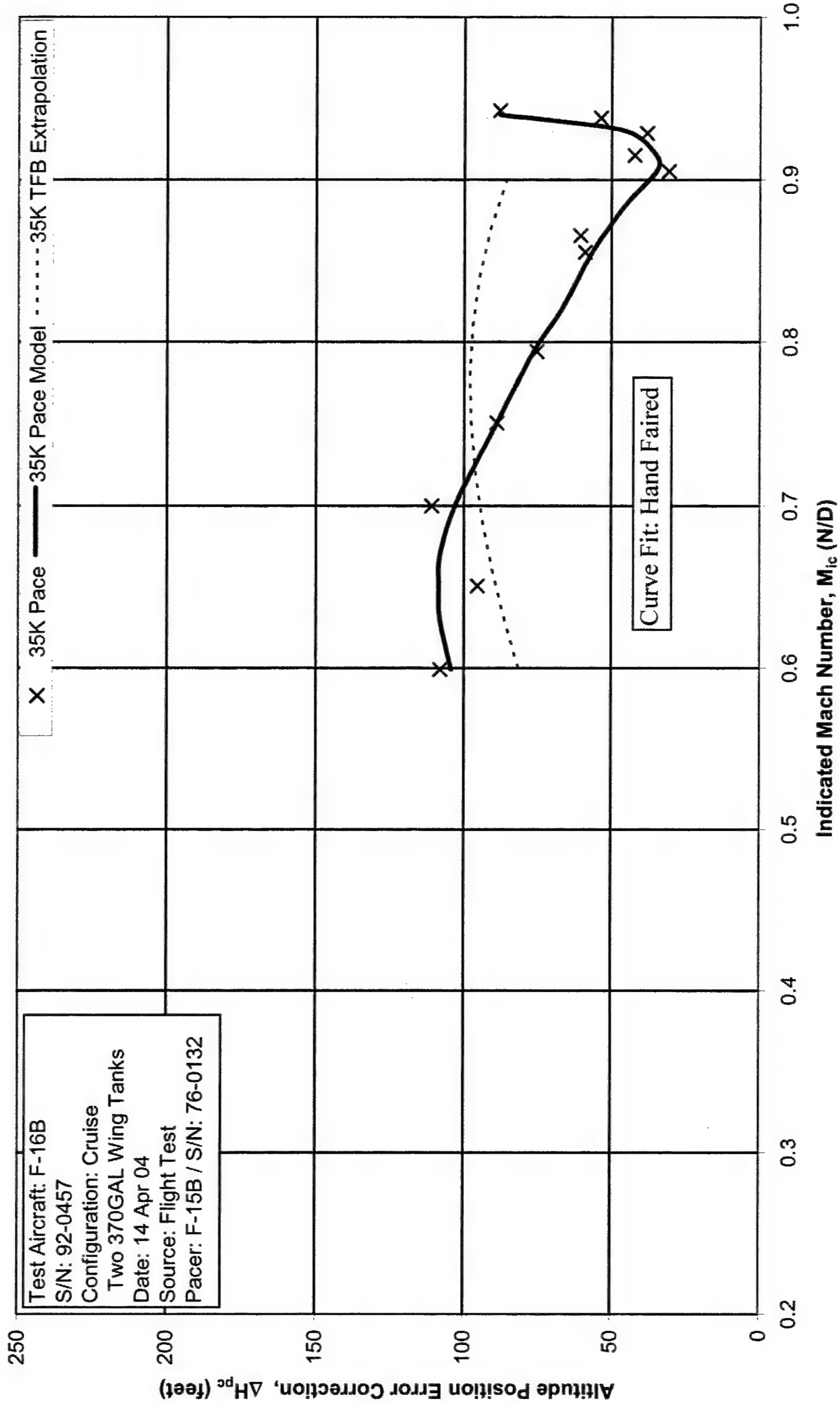


Figure 9. Altitude Position Error Correction (40,000 ft PA Pace)

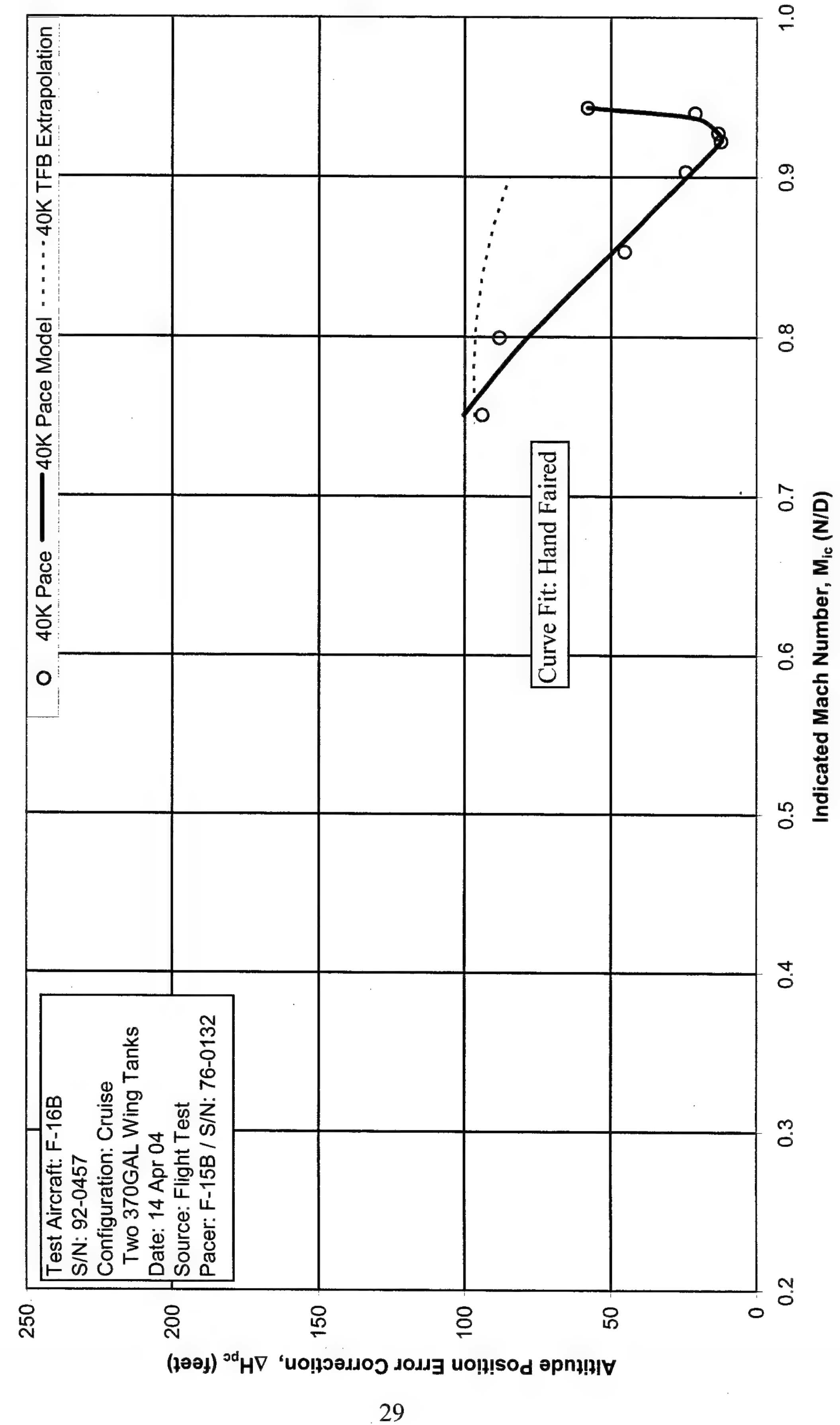


Figure 10. Altitude Position Error Correction (Tower Fly-By & Pace)

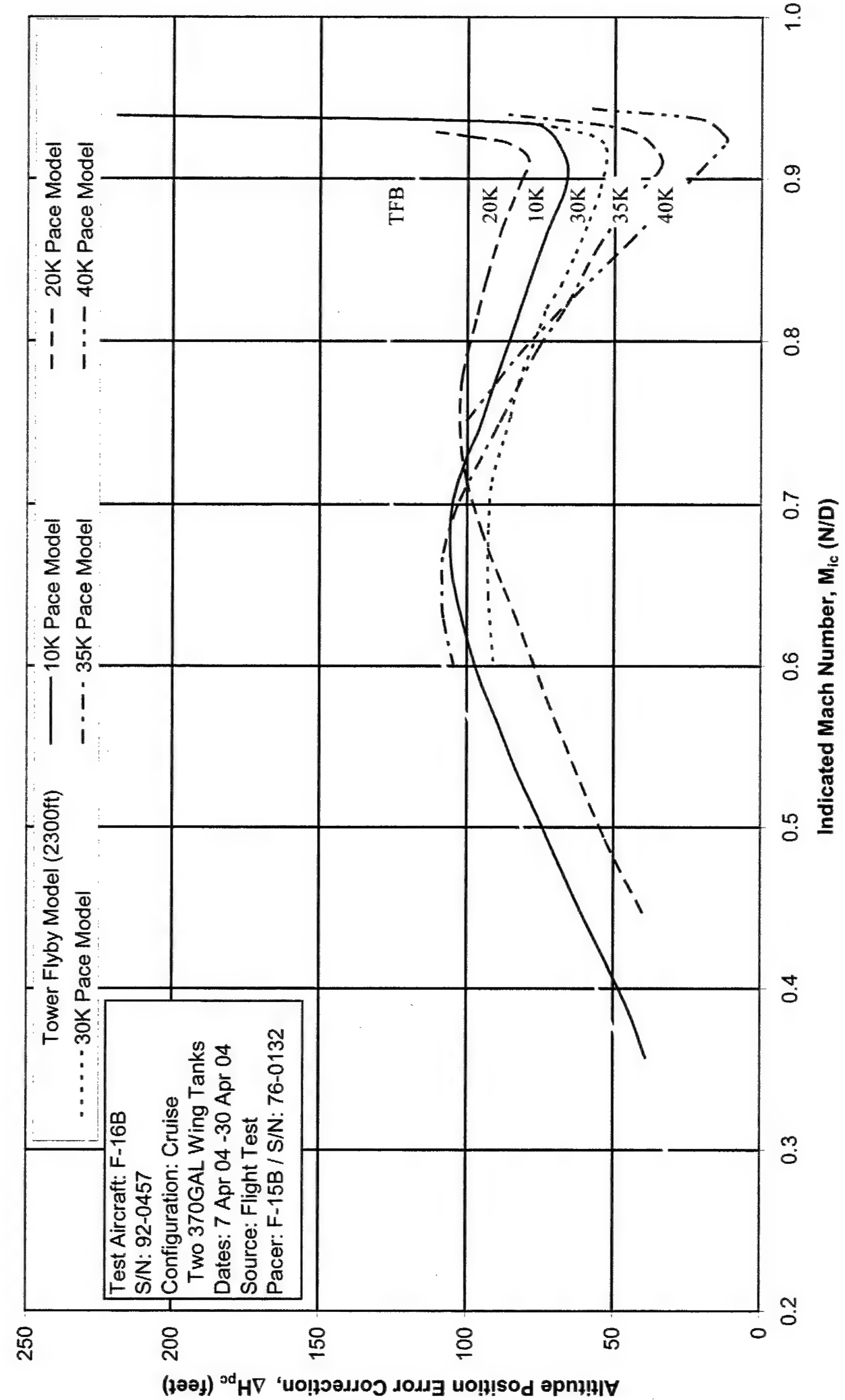


Figure 11. Altitude Position Error Correction (Tower Fly-By and Extrapolatiion)

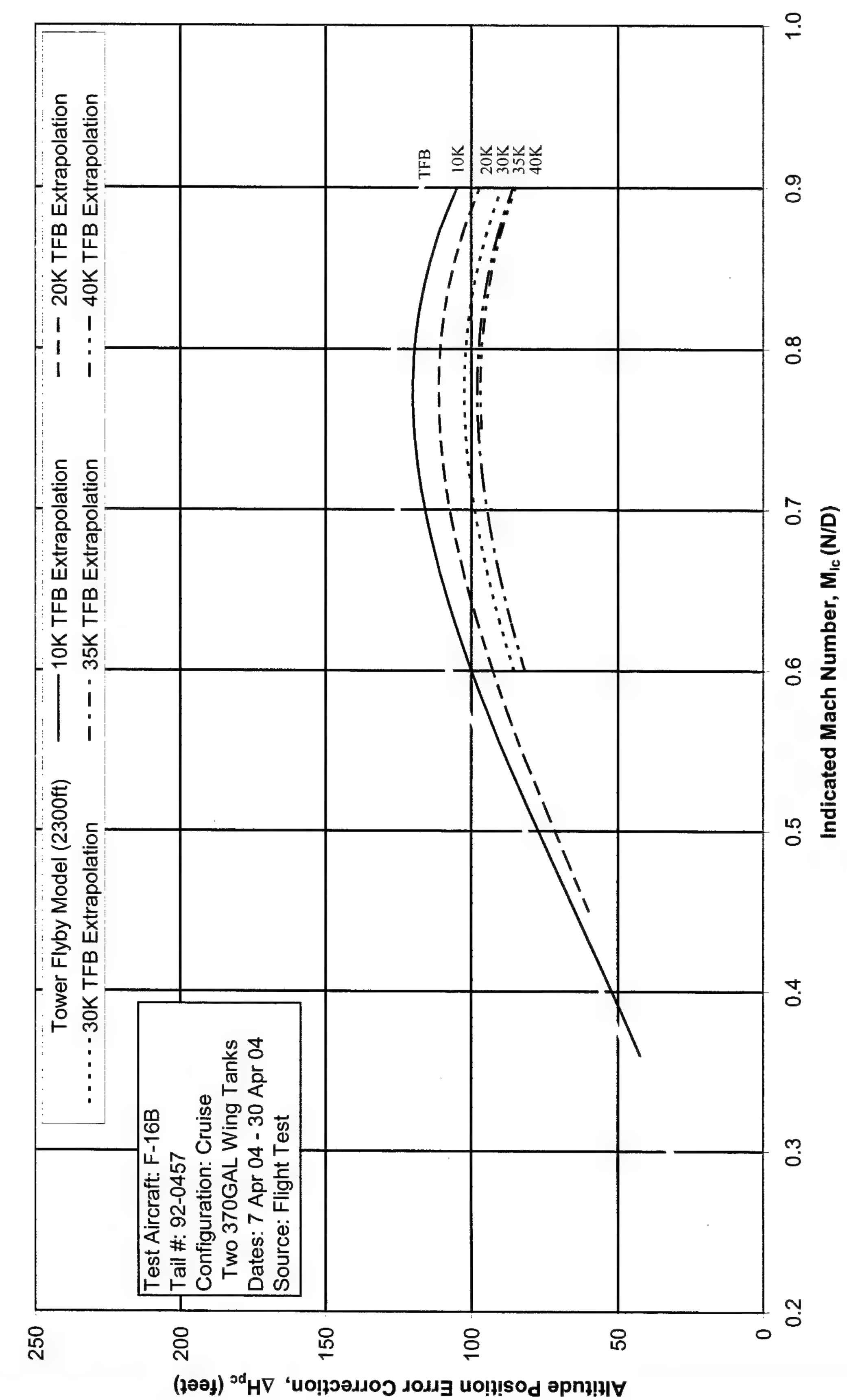


Figure 12. Altitude Position Error Correction (10,000 ft PA Cloverleaf)

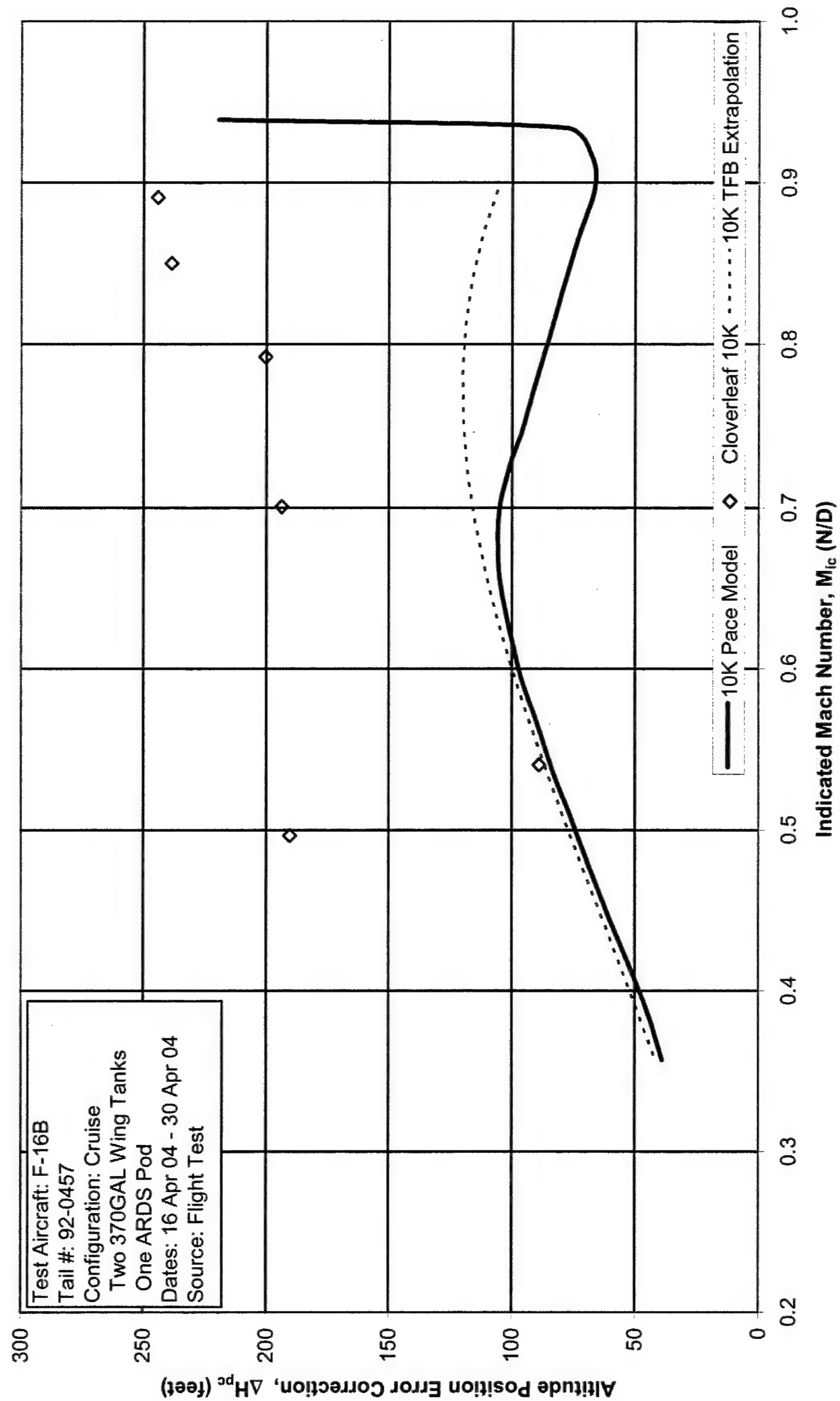


Figure 13. Altitude Position Error Correction (20,000 ft PA Cloverleaf)

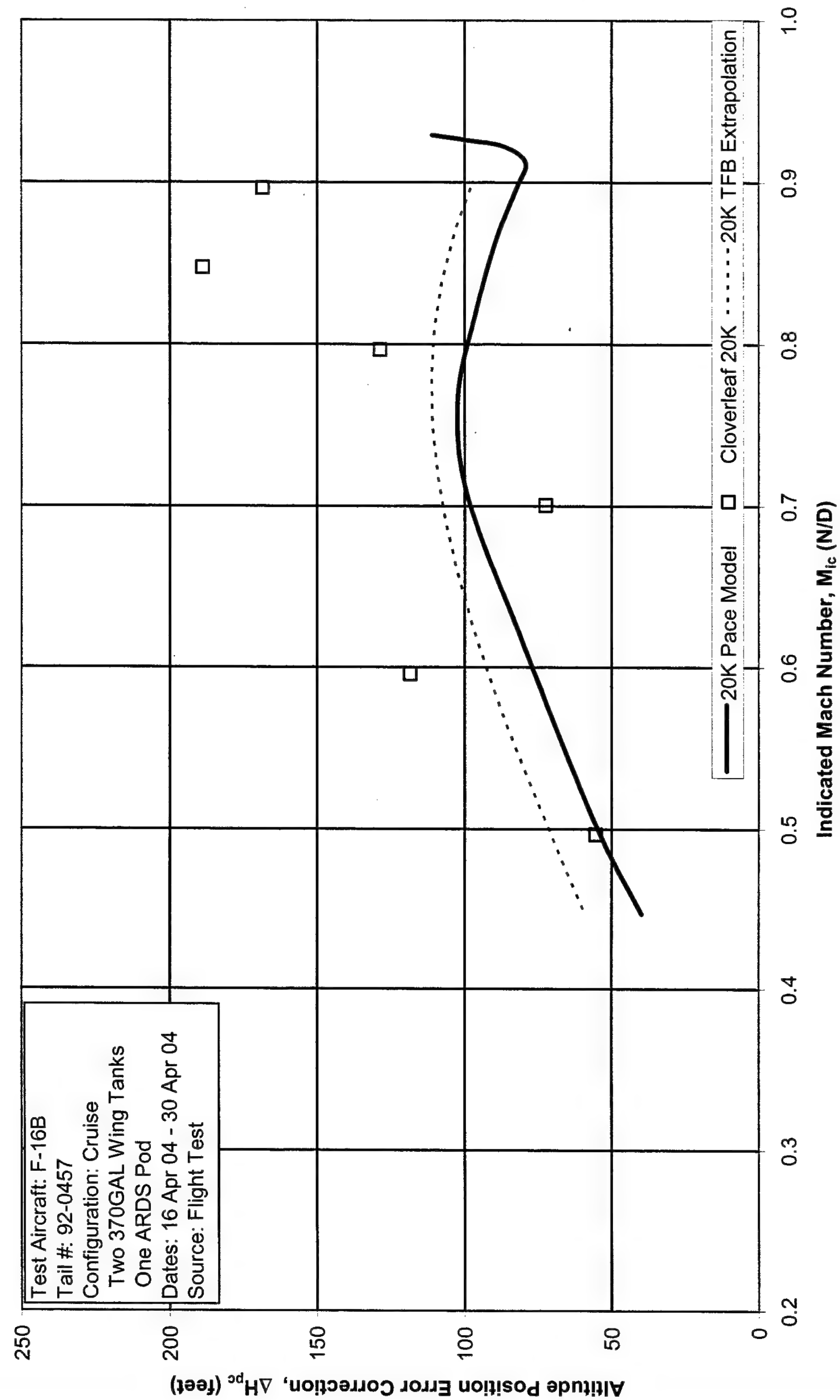


Figure 14. Altitude Position Error Correction (30,000 ft PA Cloverleaf)

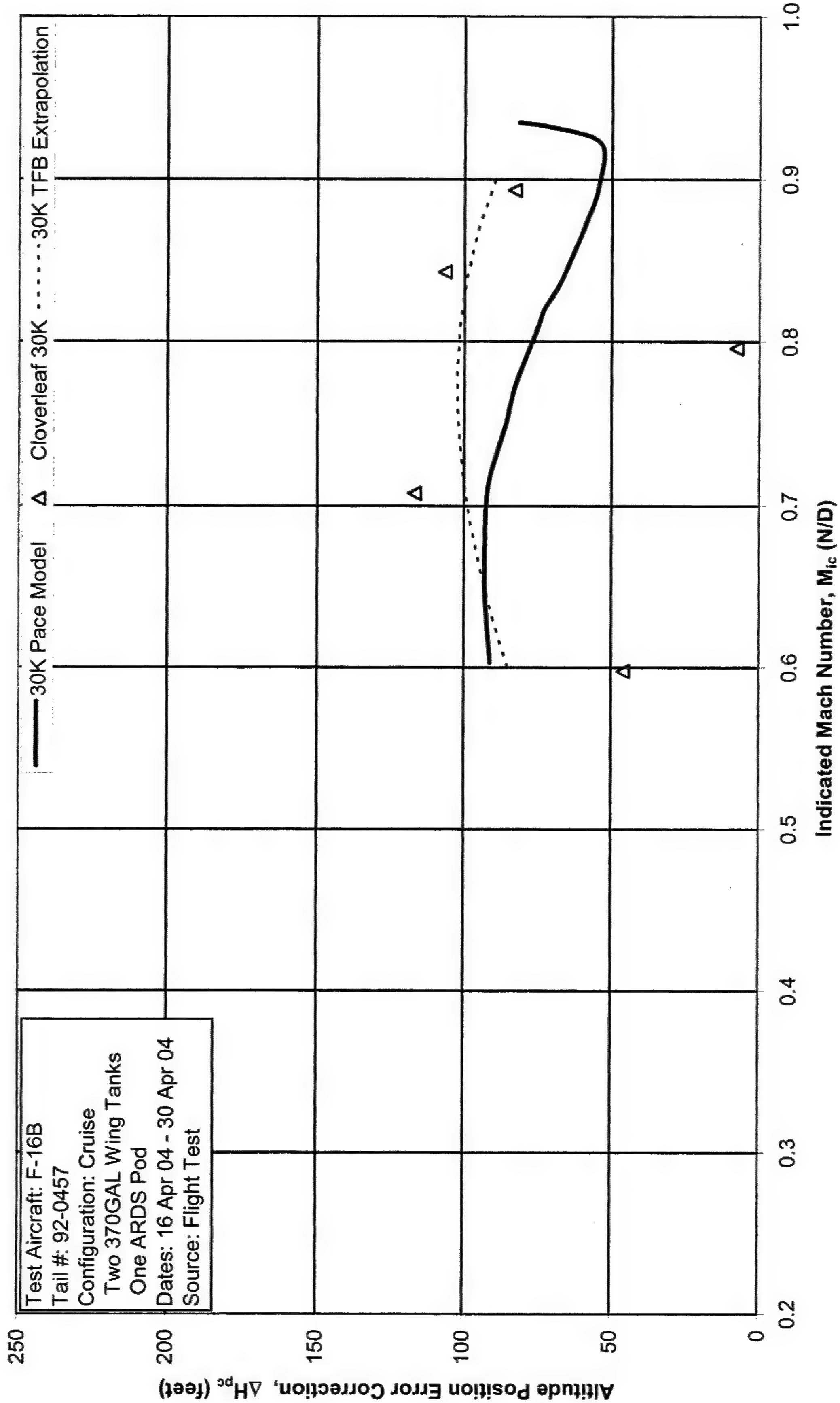


Figure 15. Altitude Position Error Correction (35,000 ft PA Cloverleaf)

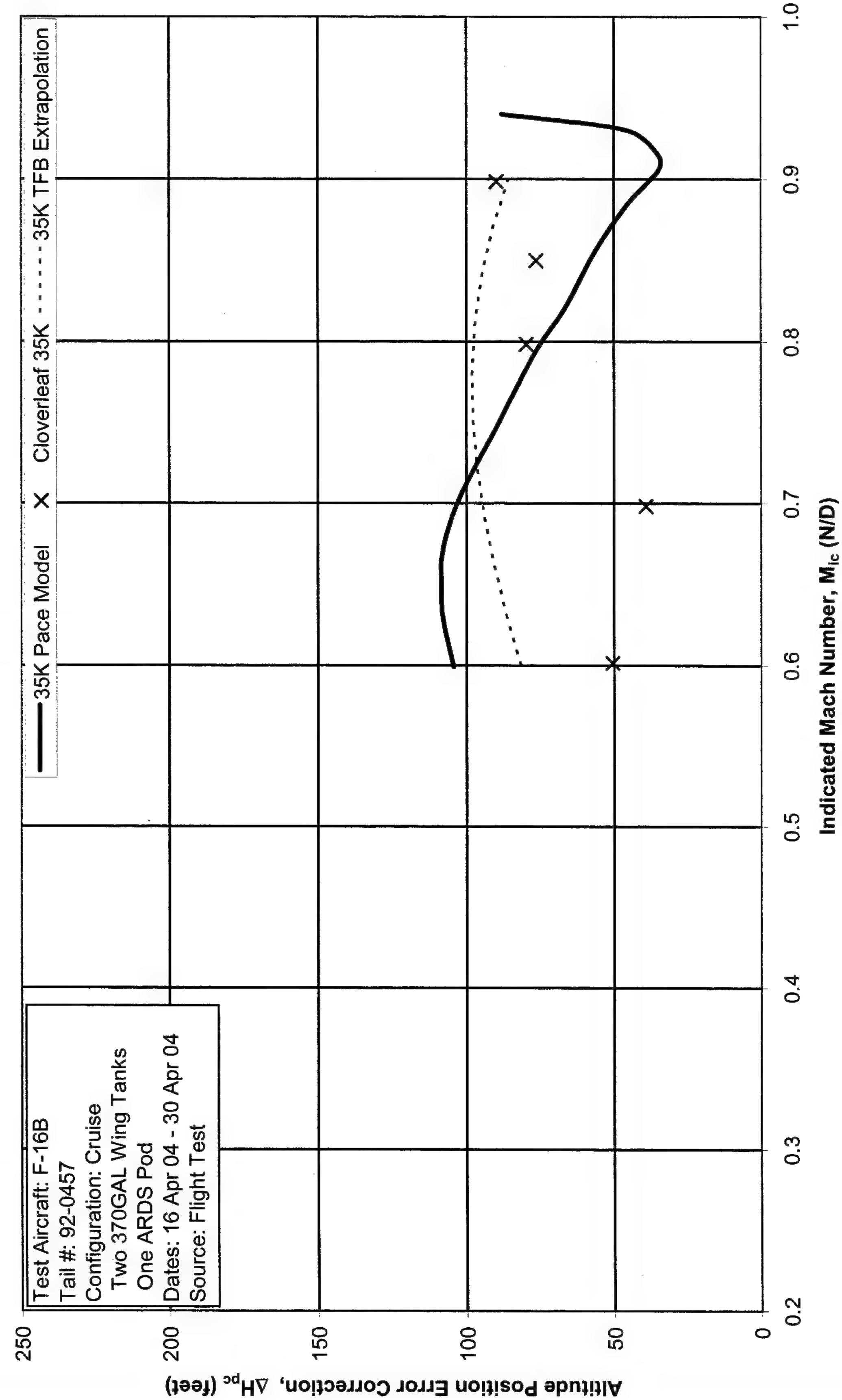


Figure 16. Altitude Position Error Correction (10,000 ft PA Level Accel/Decel)

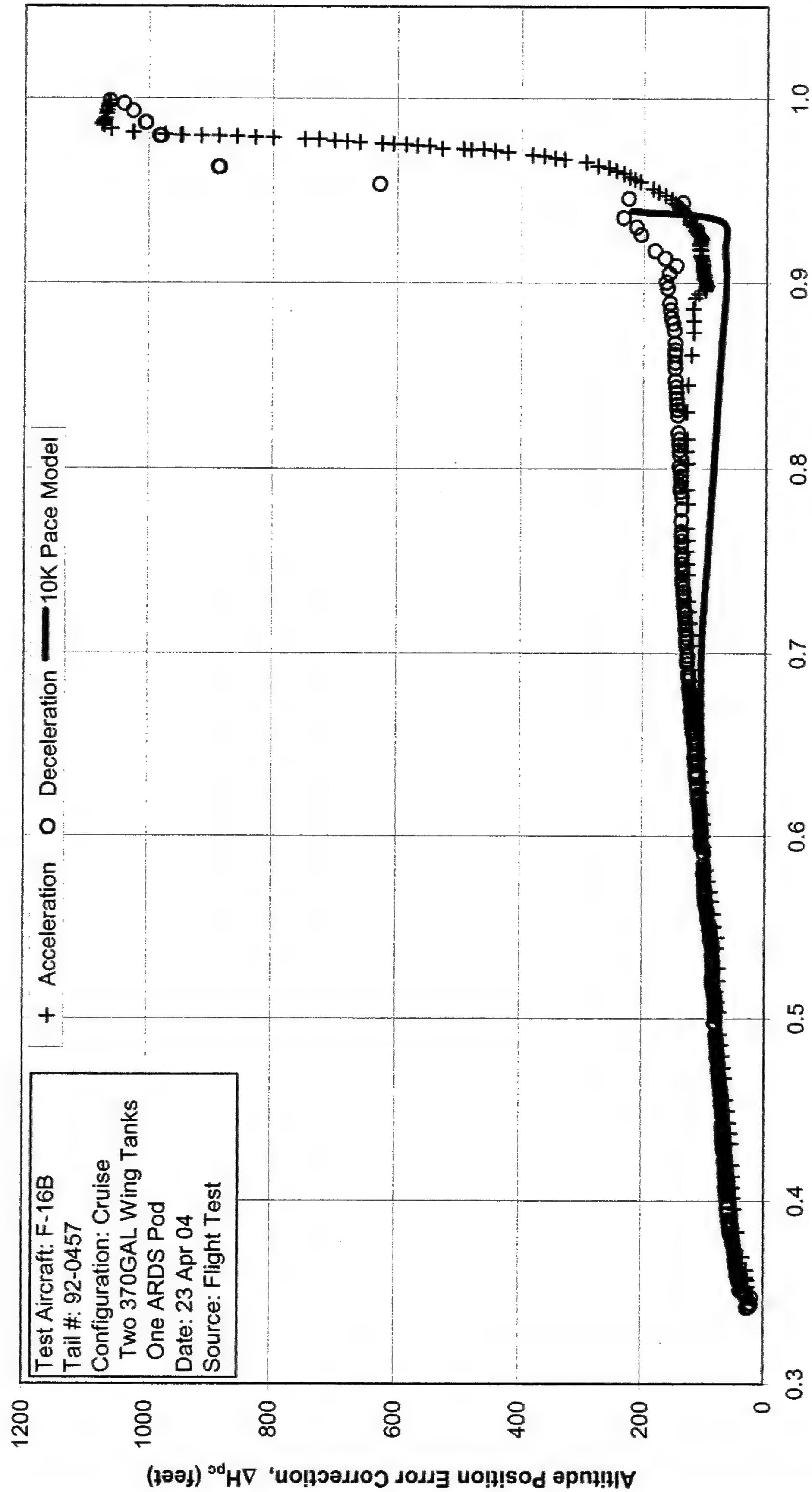


Figure 17. Altitude Position Error Correction (20,000 ft PA Level Accel/Decel)

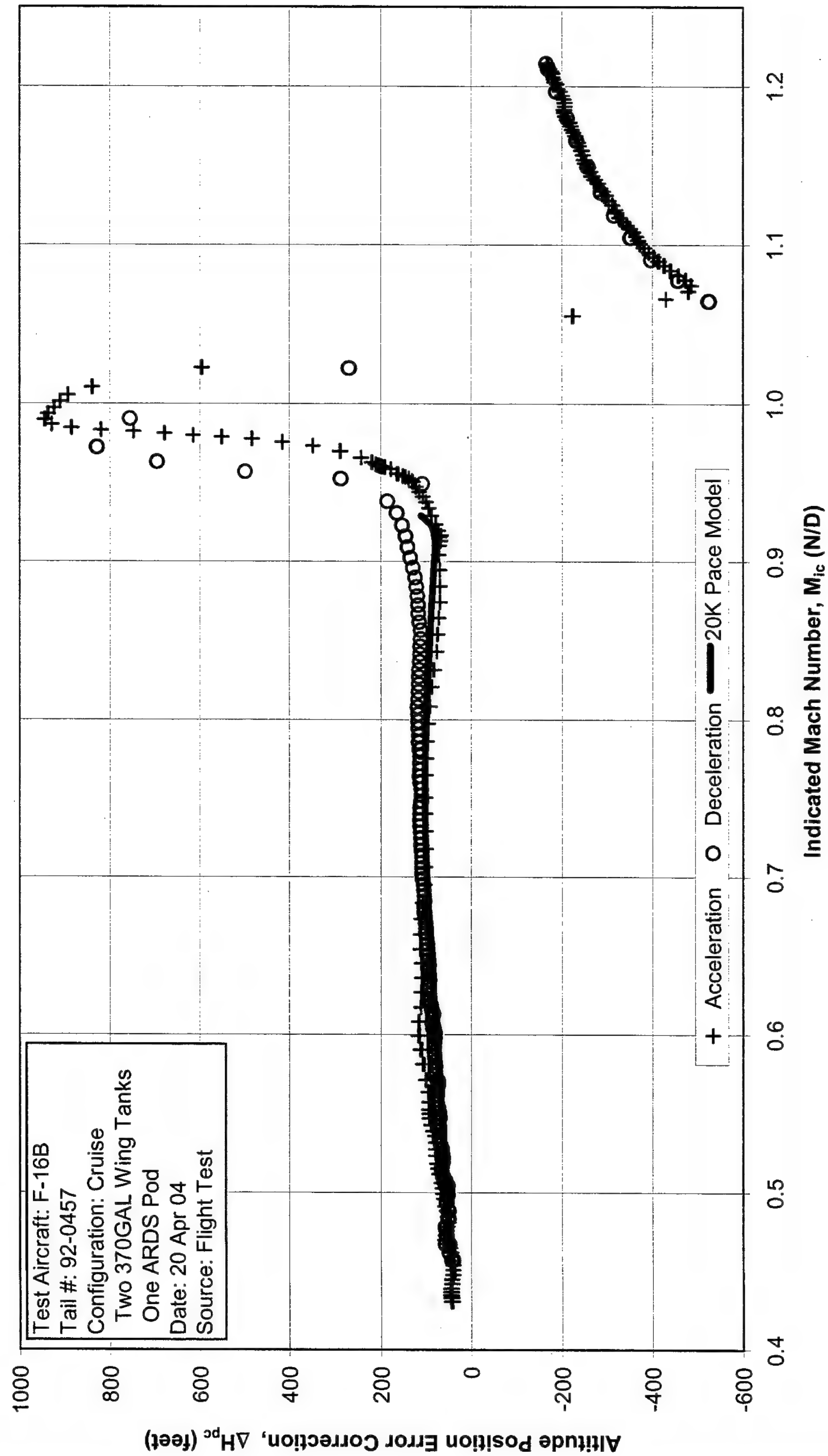


Figure 18. Altitude Position Error Correction (30,000 ft PA Level Accel/Decel)

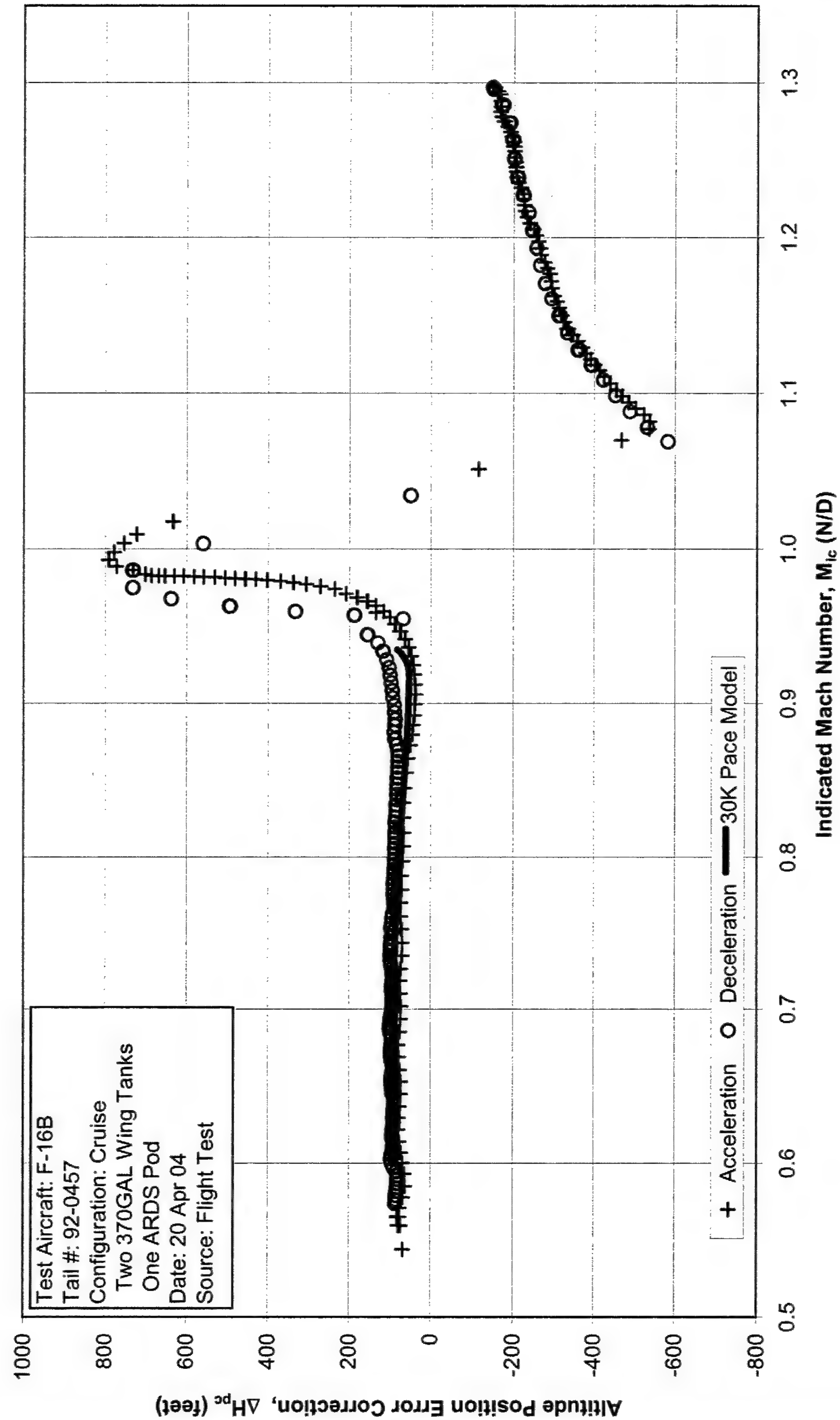


Figure 19. Altitude Position Error Correction (35,000 ft PA Level Accel/Decel)

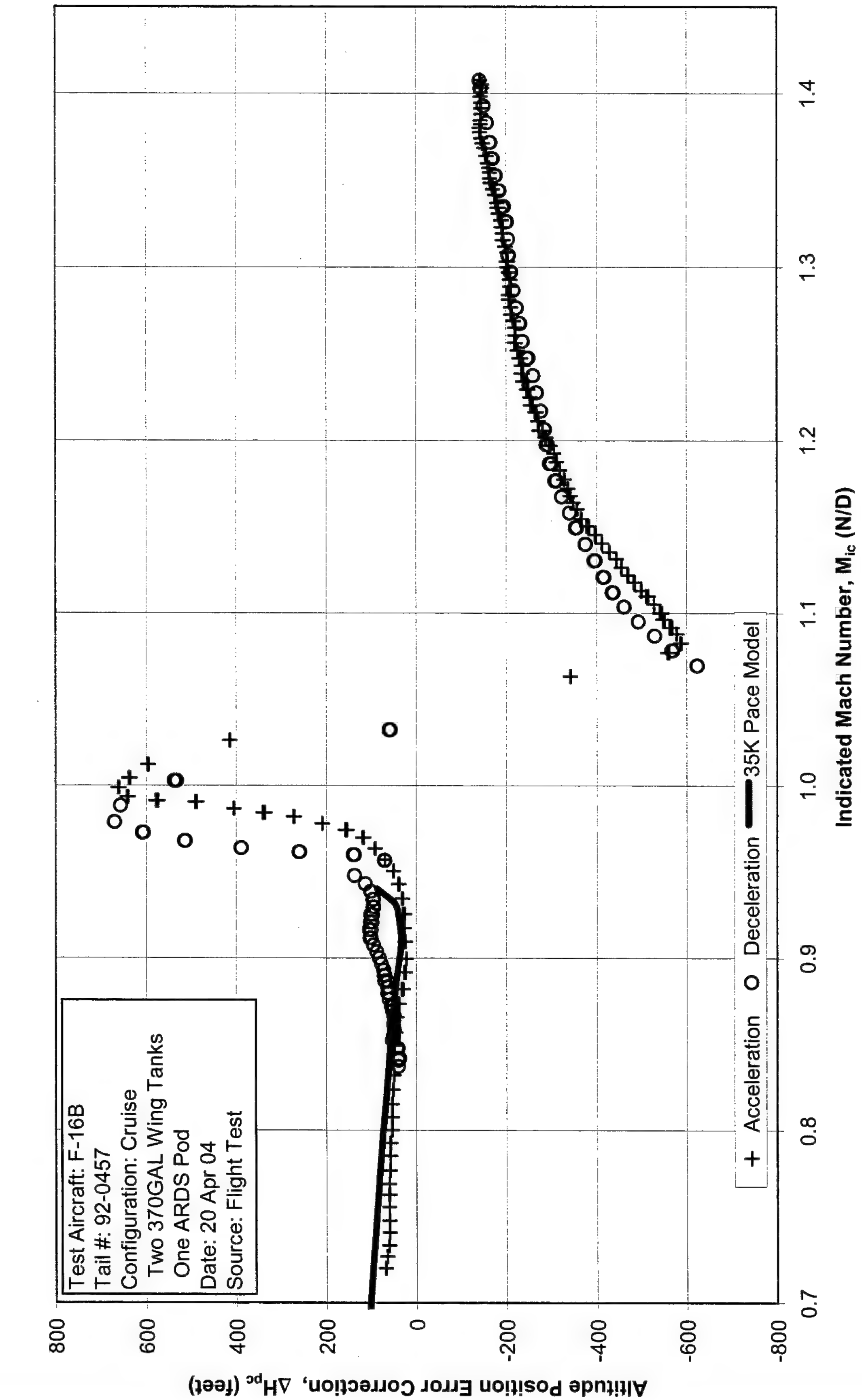


Figure 20. Altitude Position Error Correction (40,000 ft PA Level Accel/Decel)

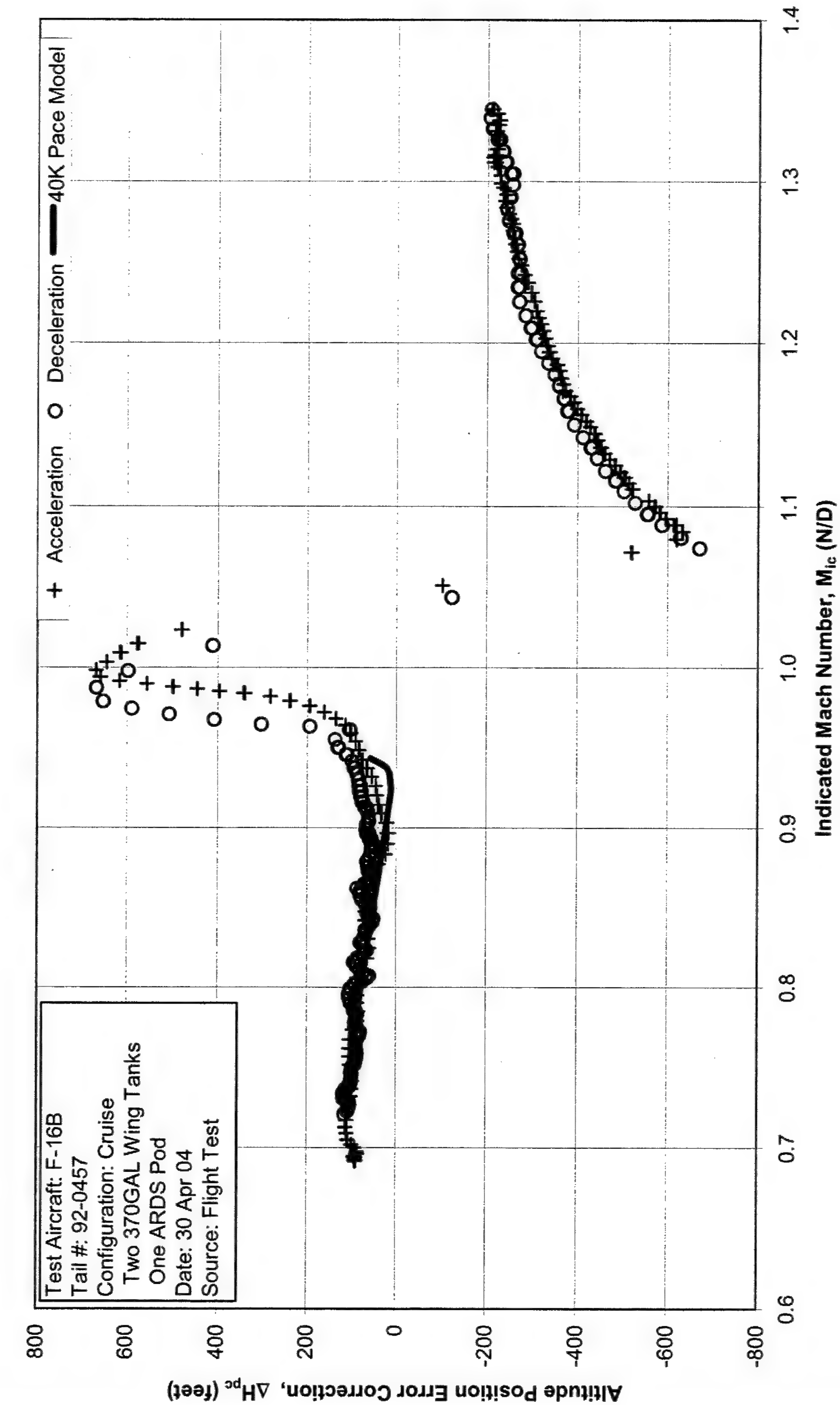


Figure 21. Engine Airflow Effects (10,000 ft PA Level Accel/Decel)

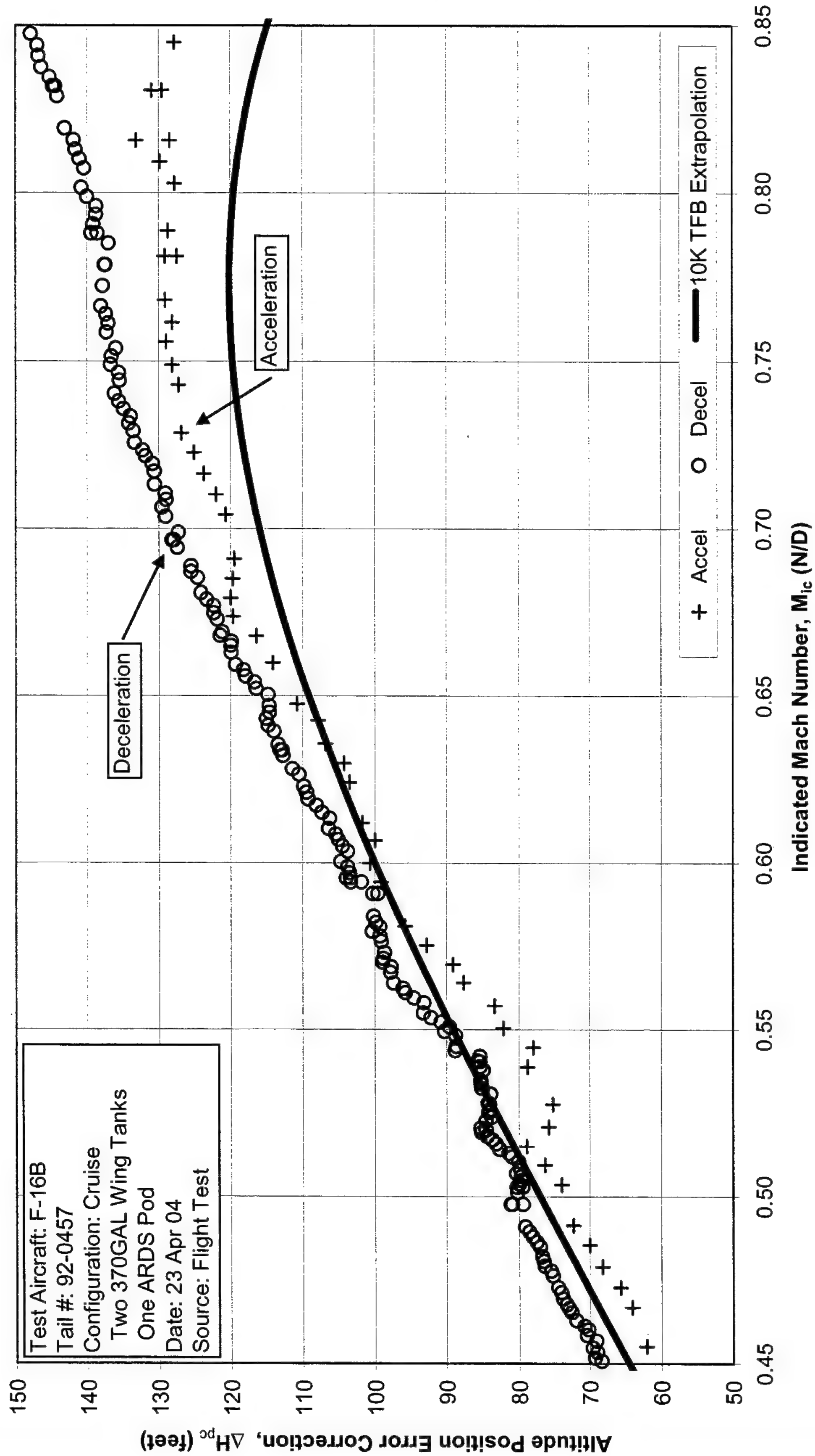


Figure 22. Altitude Position Error Correction (10,000 ft PA Constant Airspeed Turn)

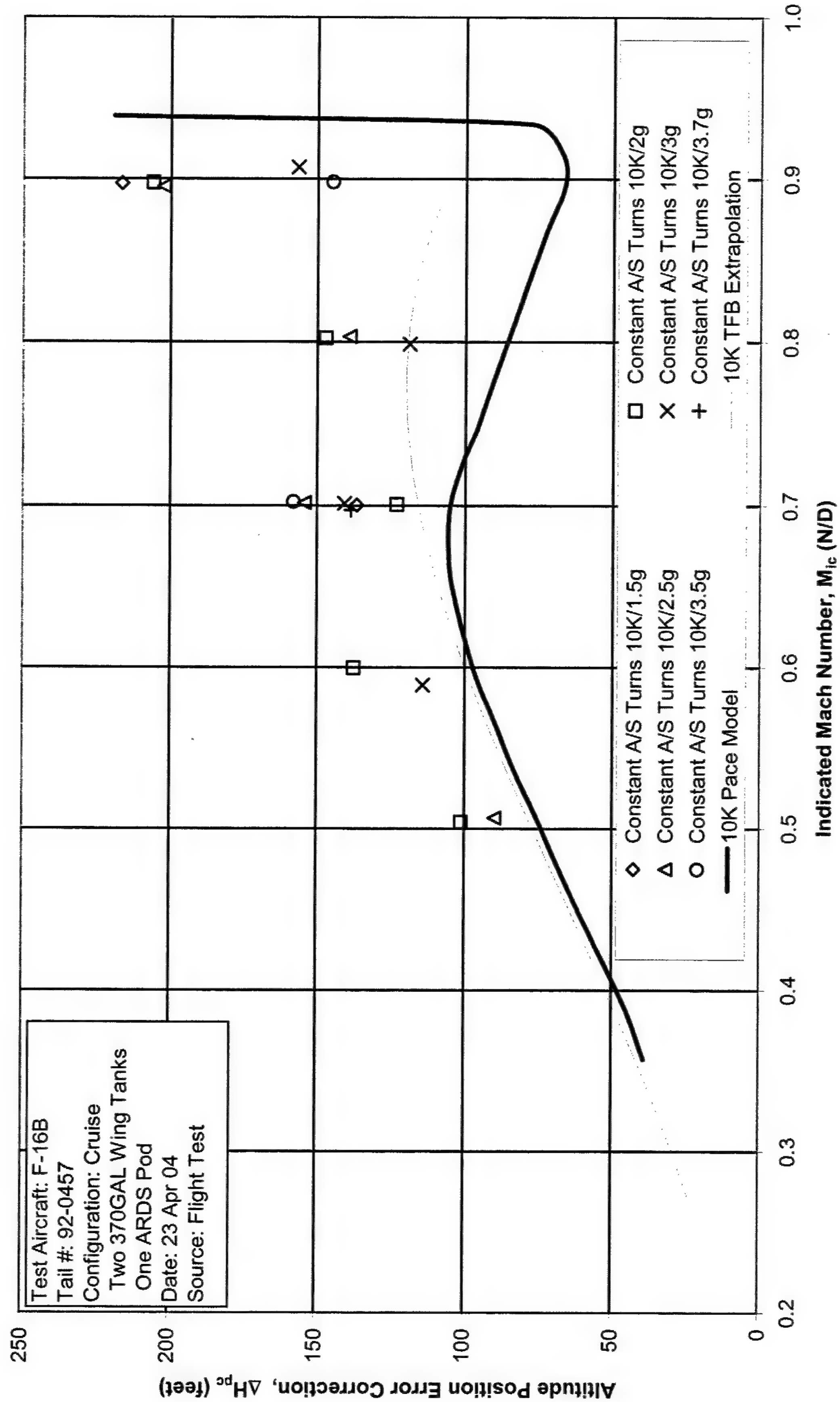


Figure 23. Zero Total Pressure Validation

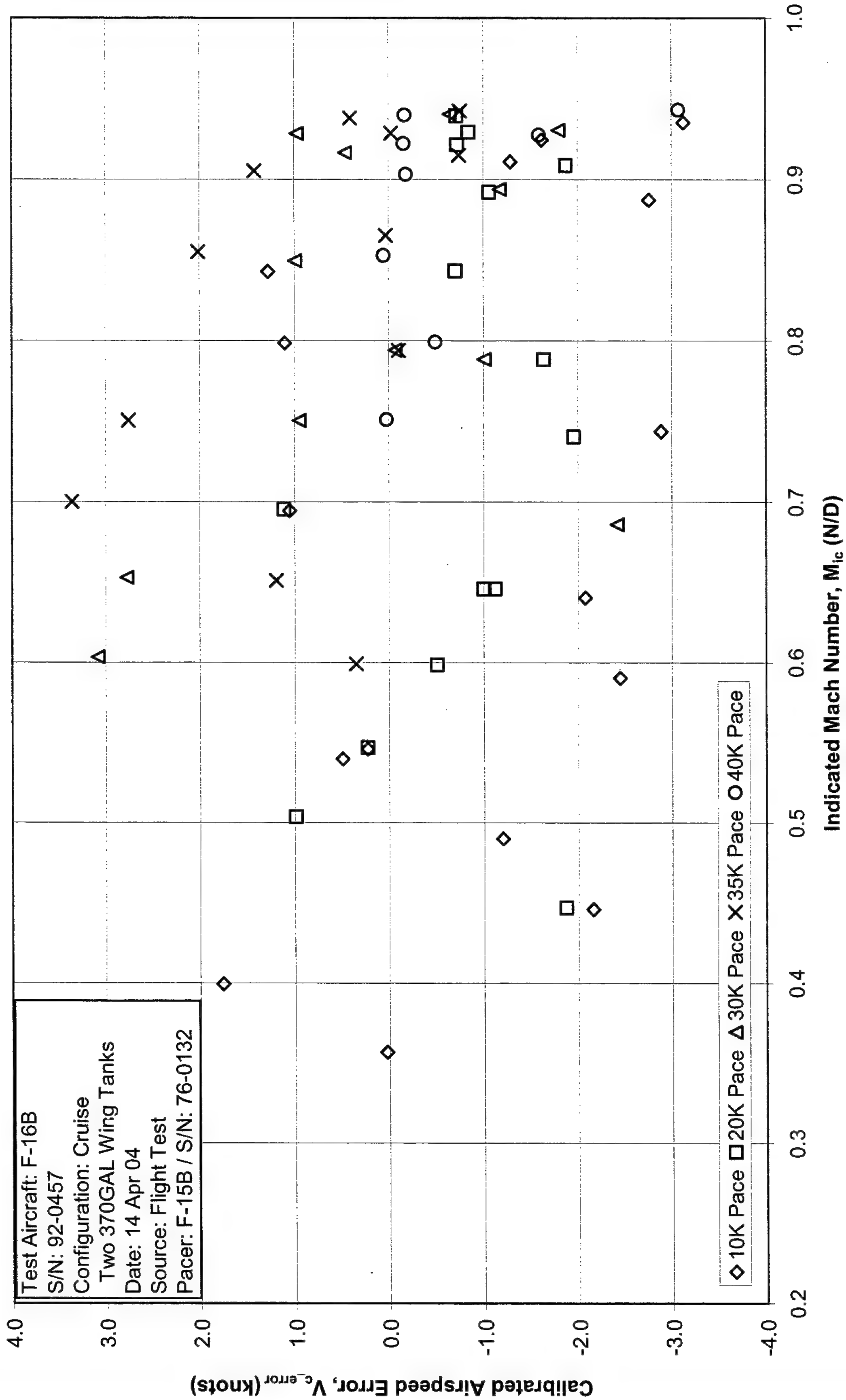


Figure 24. Airspeed Position Error Correction (Tower Fly-By)

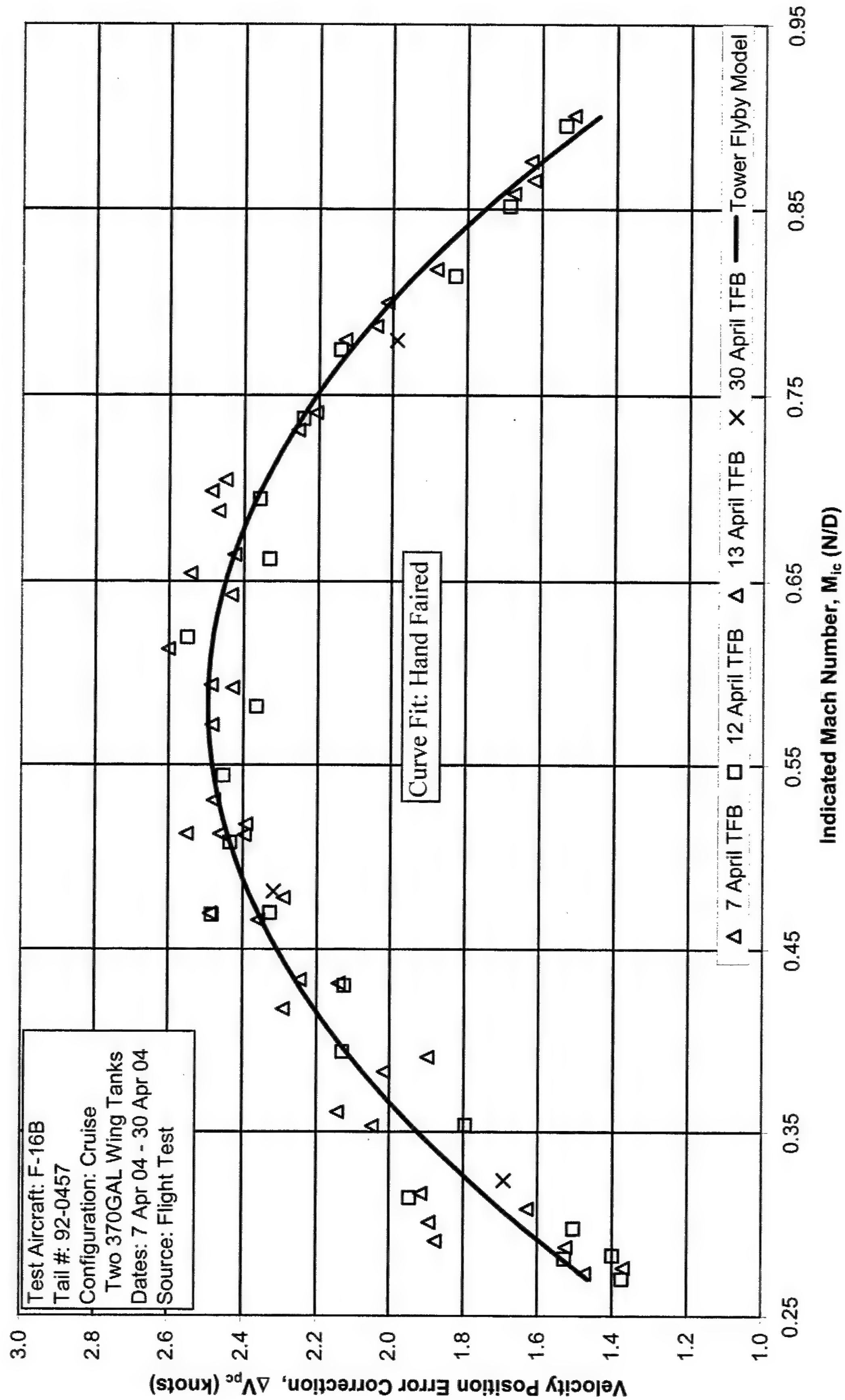


Figure 25. Airspeed Position Error Correction (10,000 ft PA Pace)

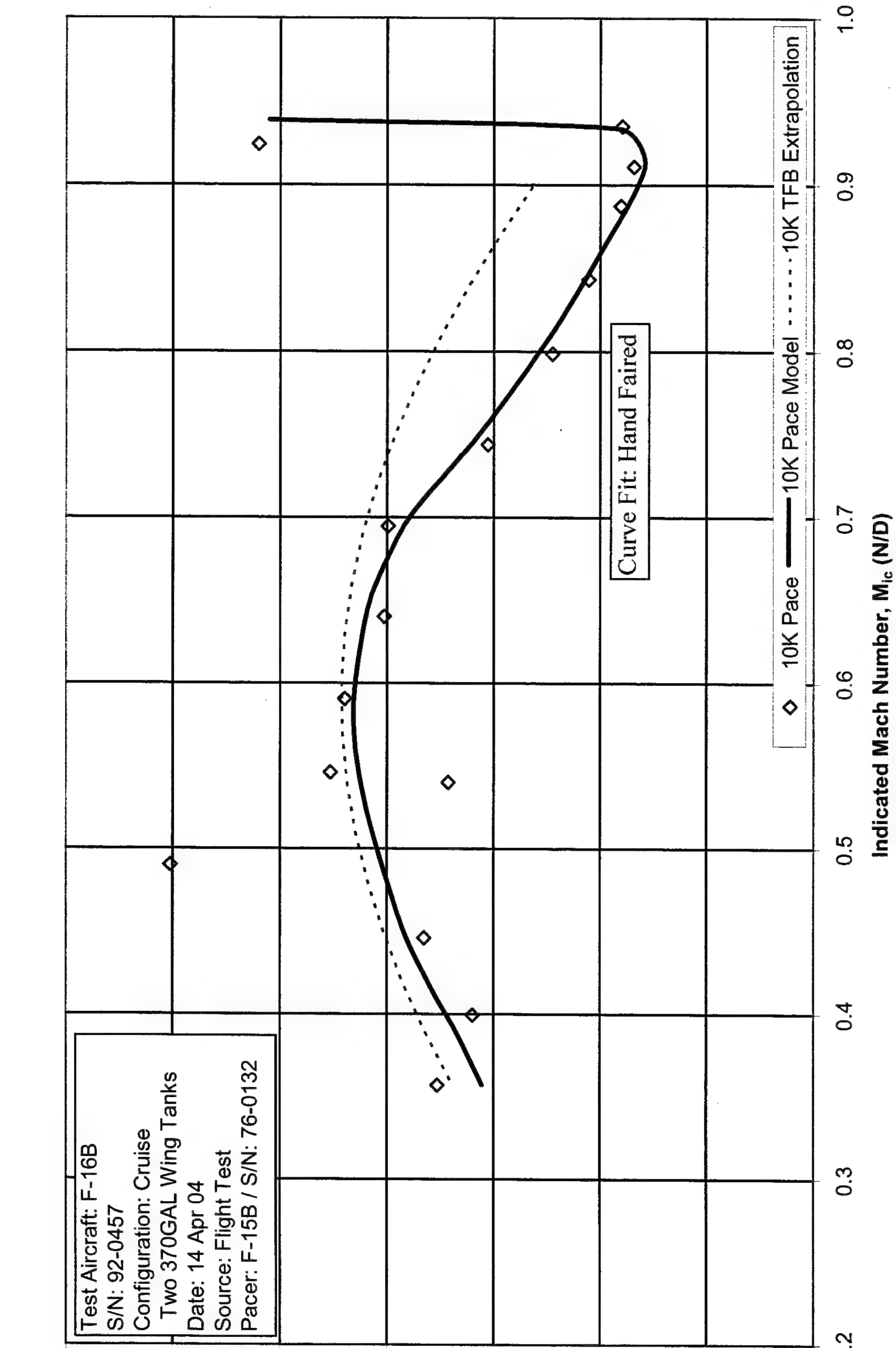


Figure 26. Airspeed Position Error Correction (20,000 ft PA Pace)

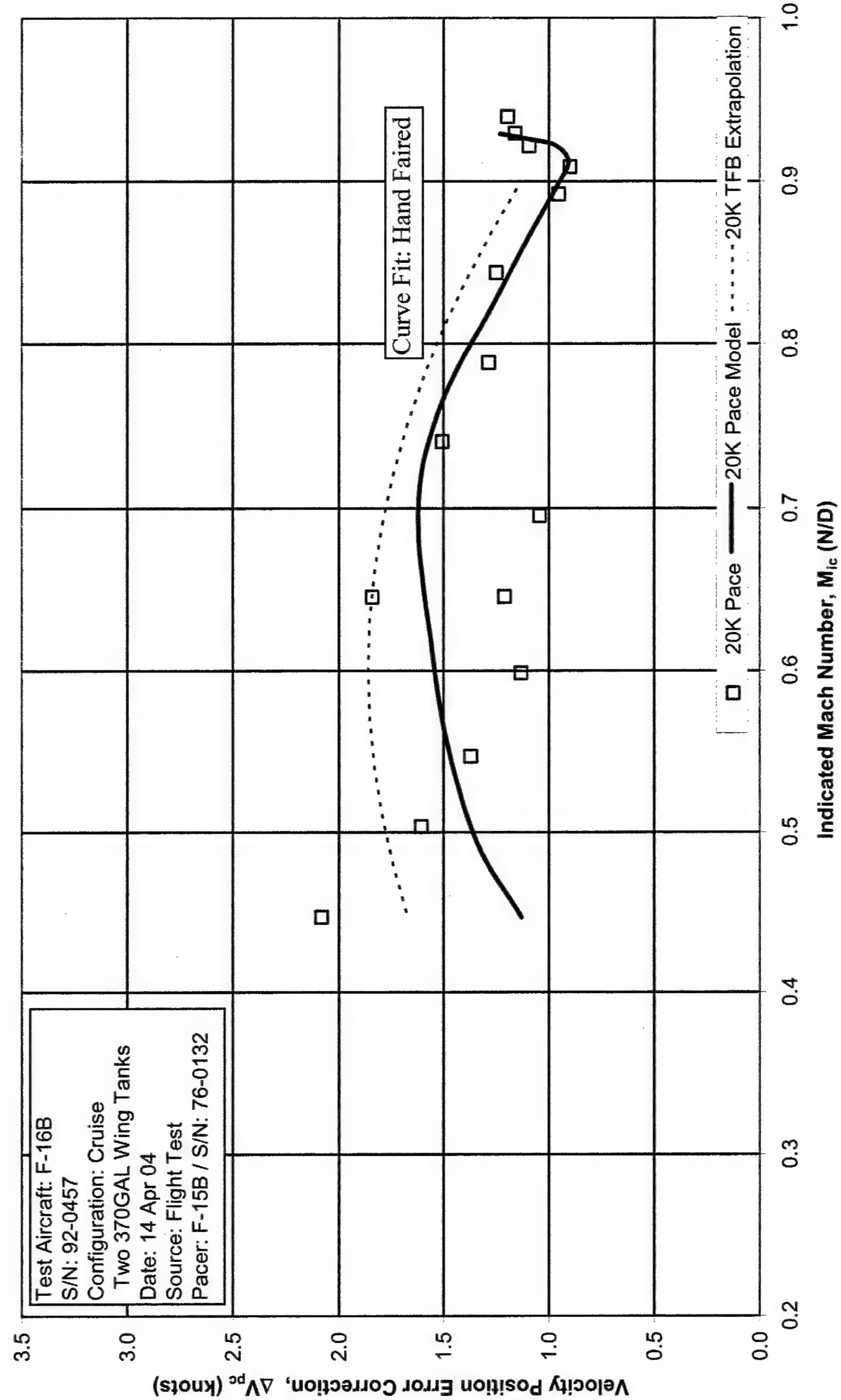


Figure 27. Airspeed Position Error Correction (30,000 ft PA Pace)

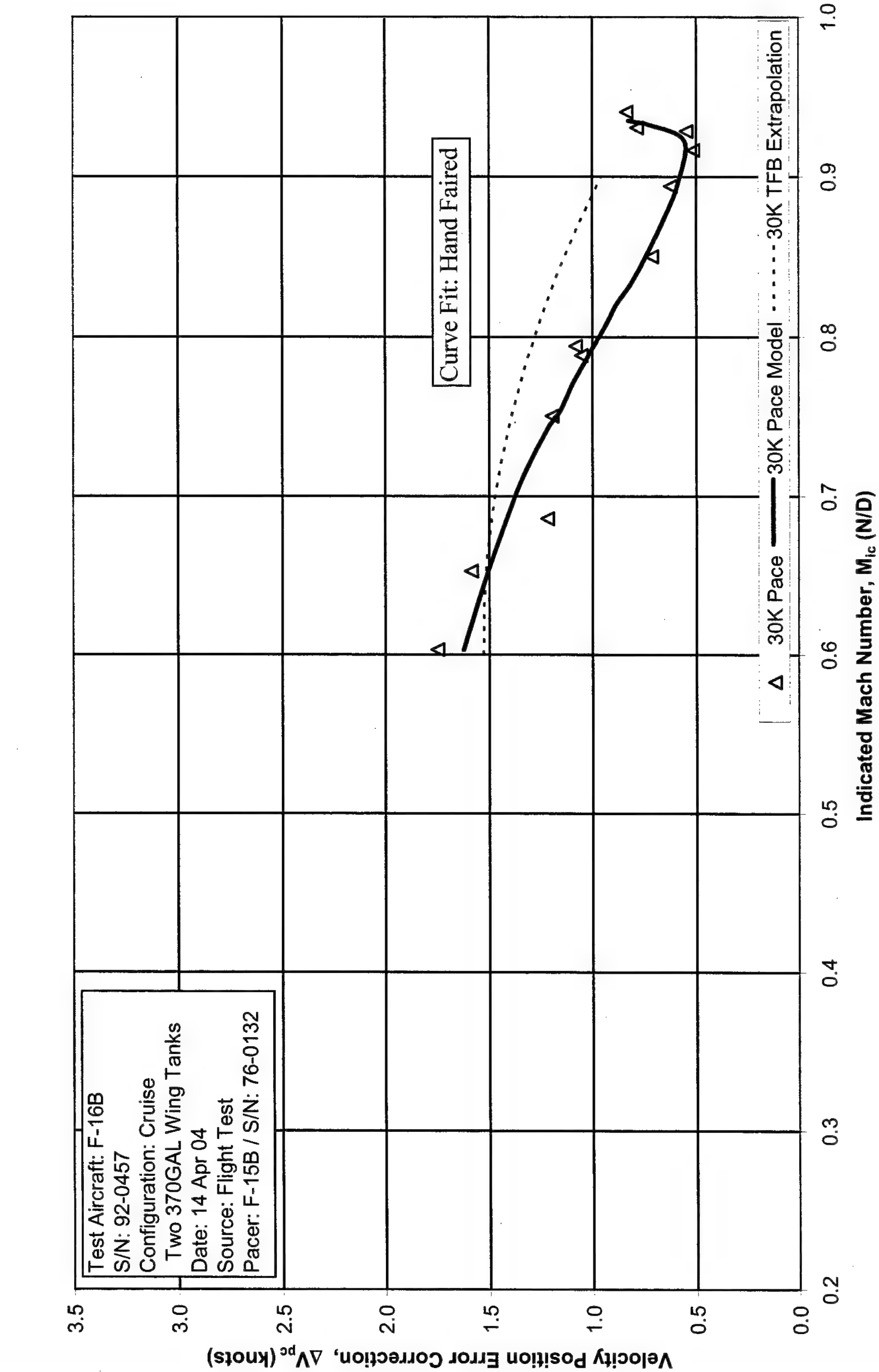


Figure 28. Airspeed Position Error Correction (35,000 ft PA Pace)

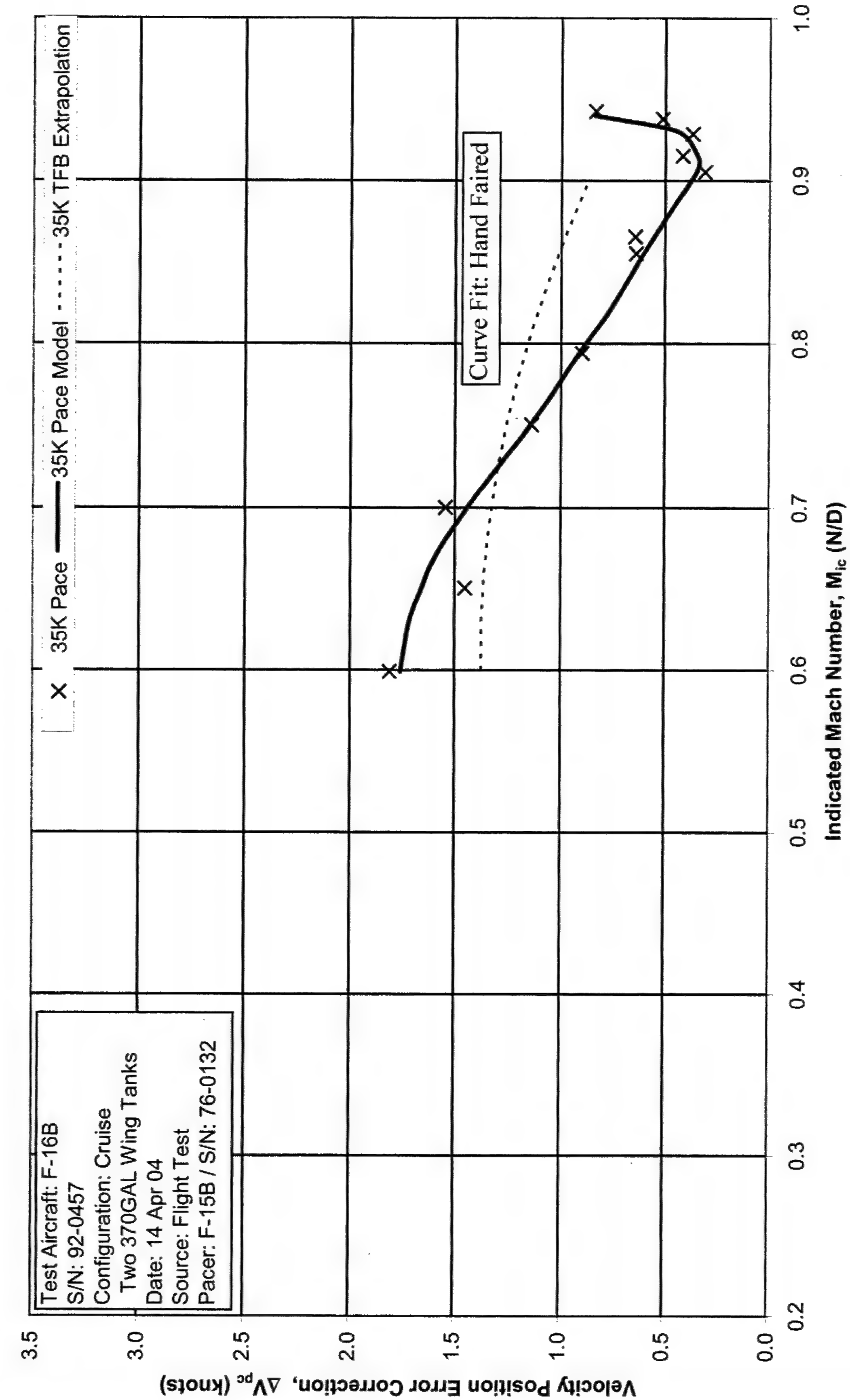


Figure 29. Airspeed Position Error Correction (40,000 ft PA Pace)

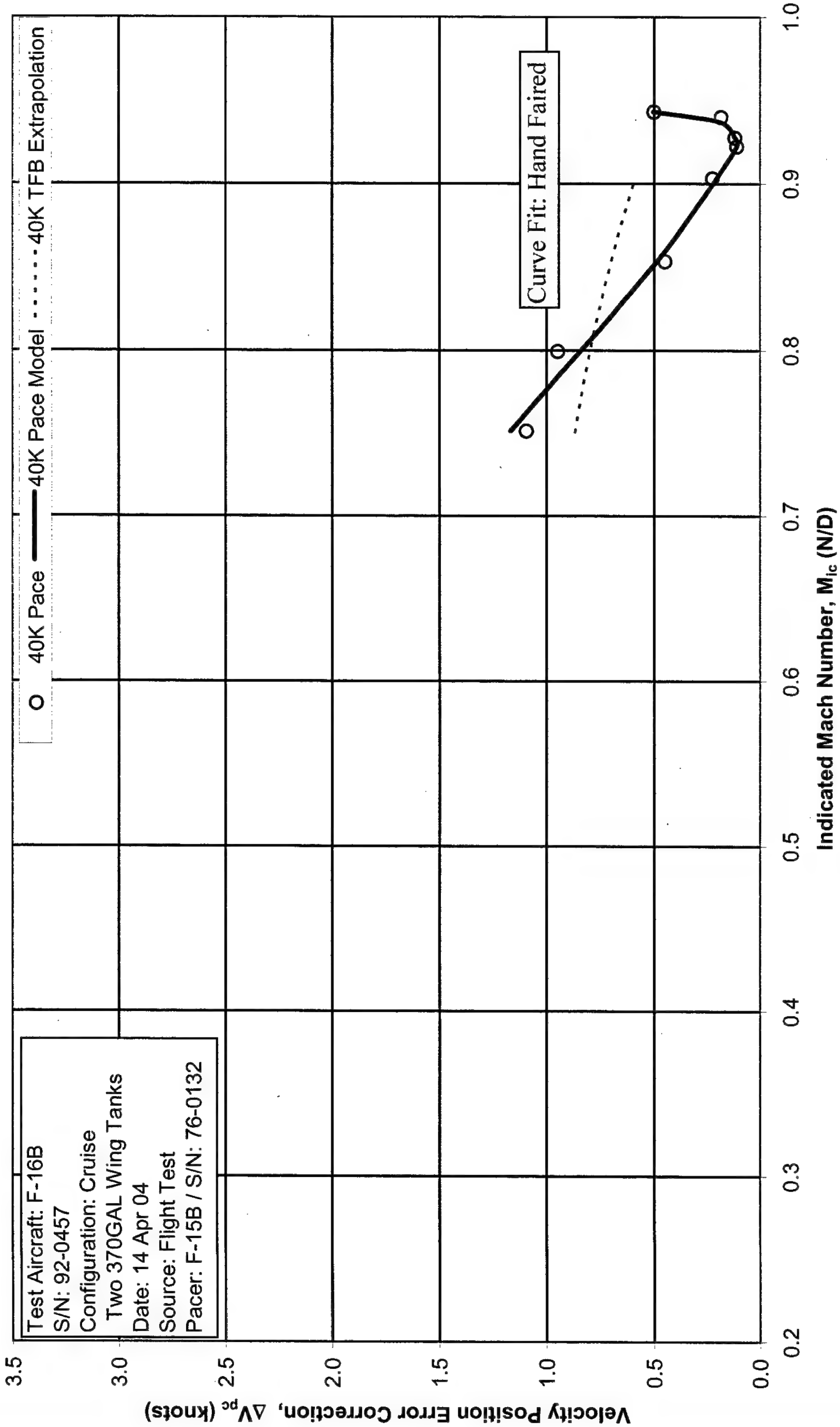


Figure 30. Airspeed Position Error Correction (Tower Fly-By & Pace)

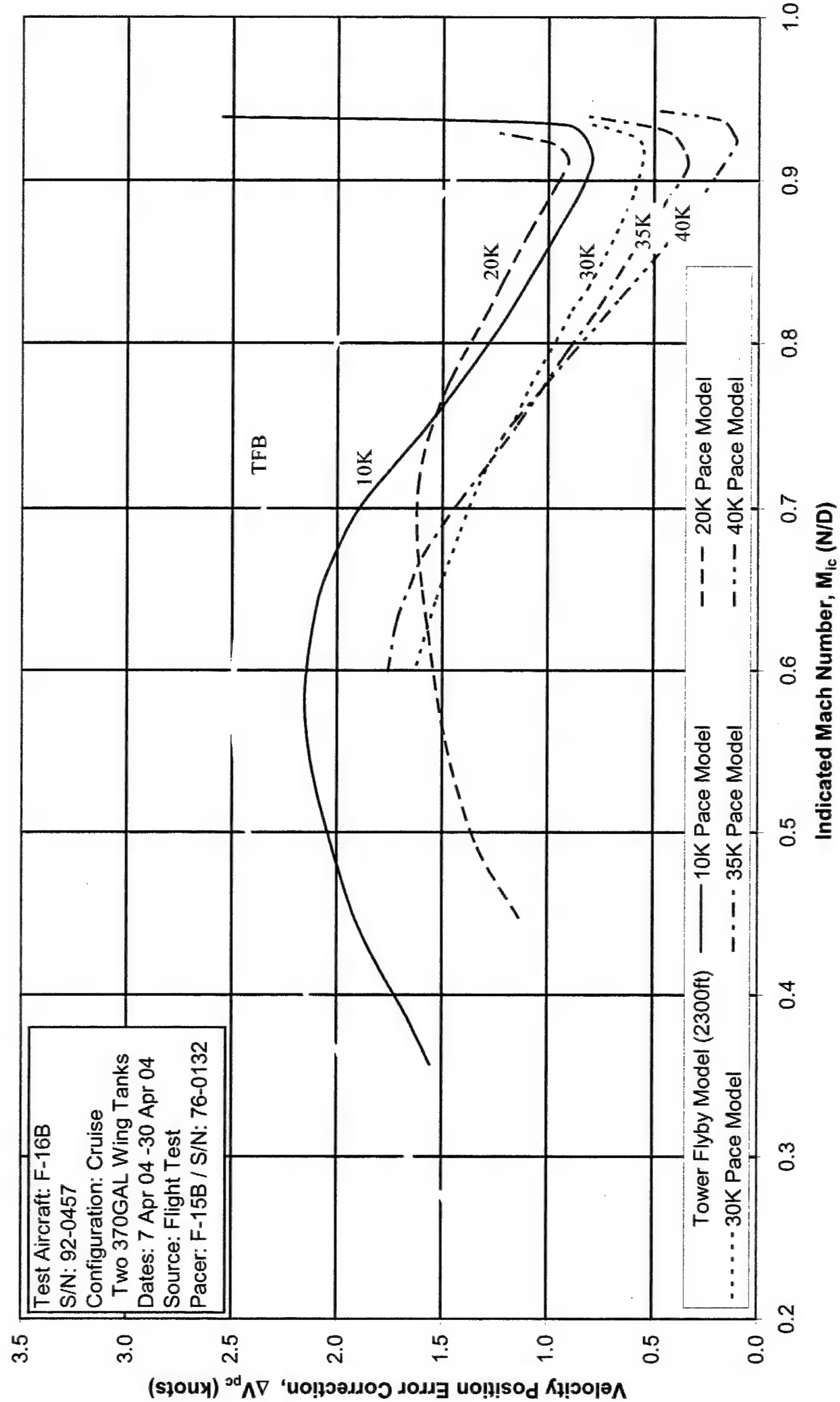


Figure 31. Airspeed Position Error Correction (Tower Fly-By and Extrapolated)

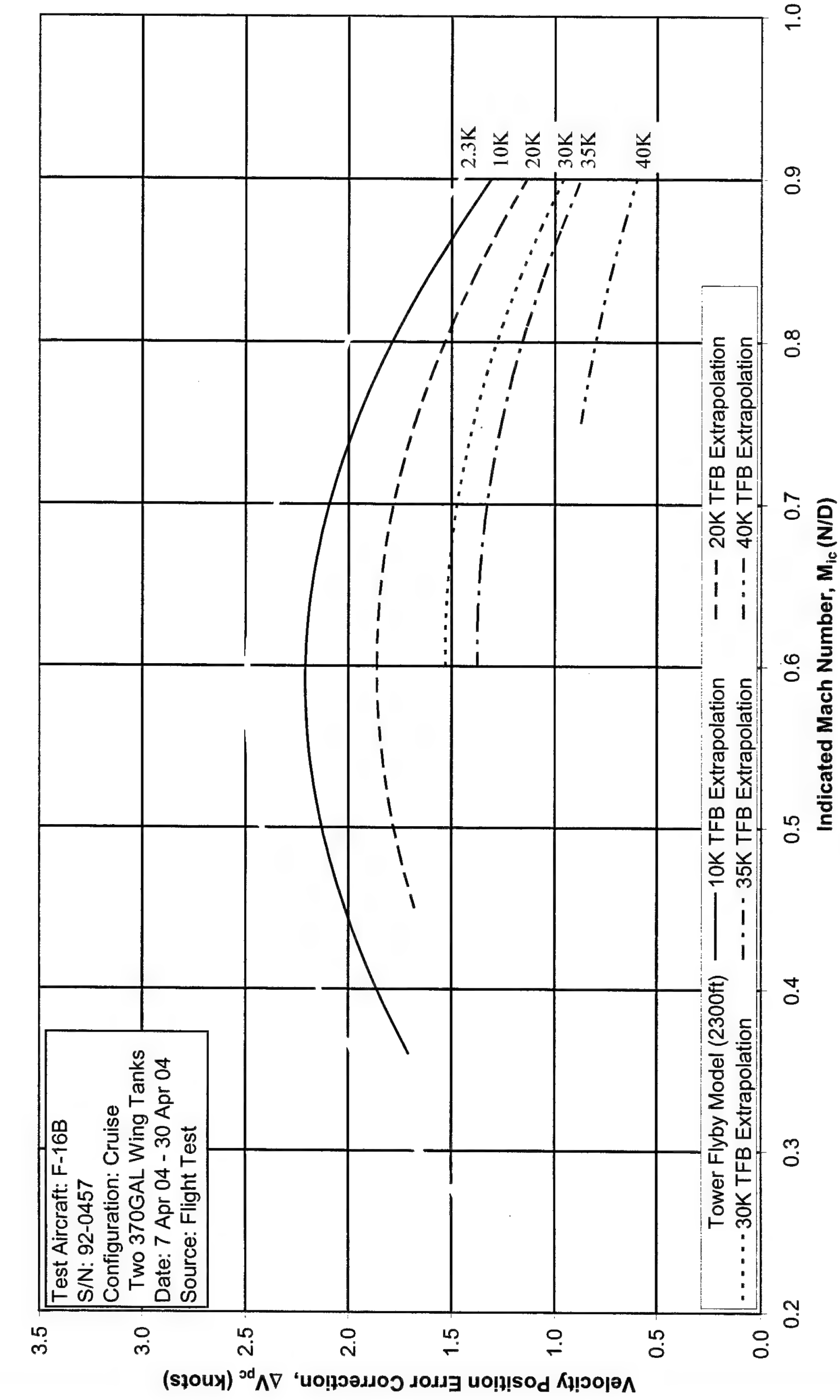


Figure 32. Airspeed Position Error Correction (10,000 ft PA Cloverleaf)

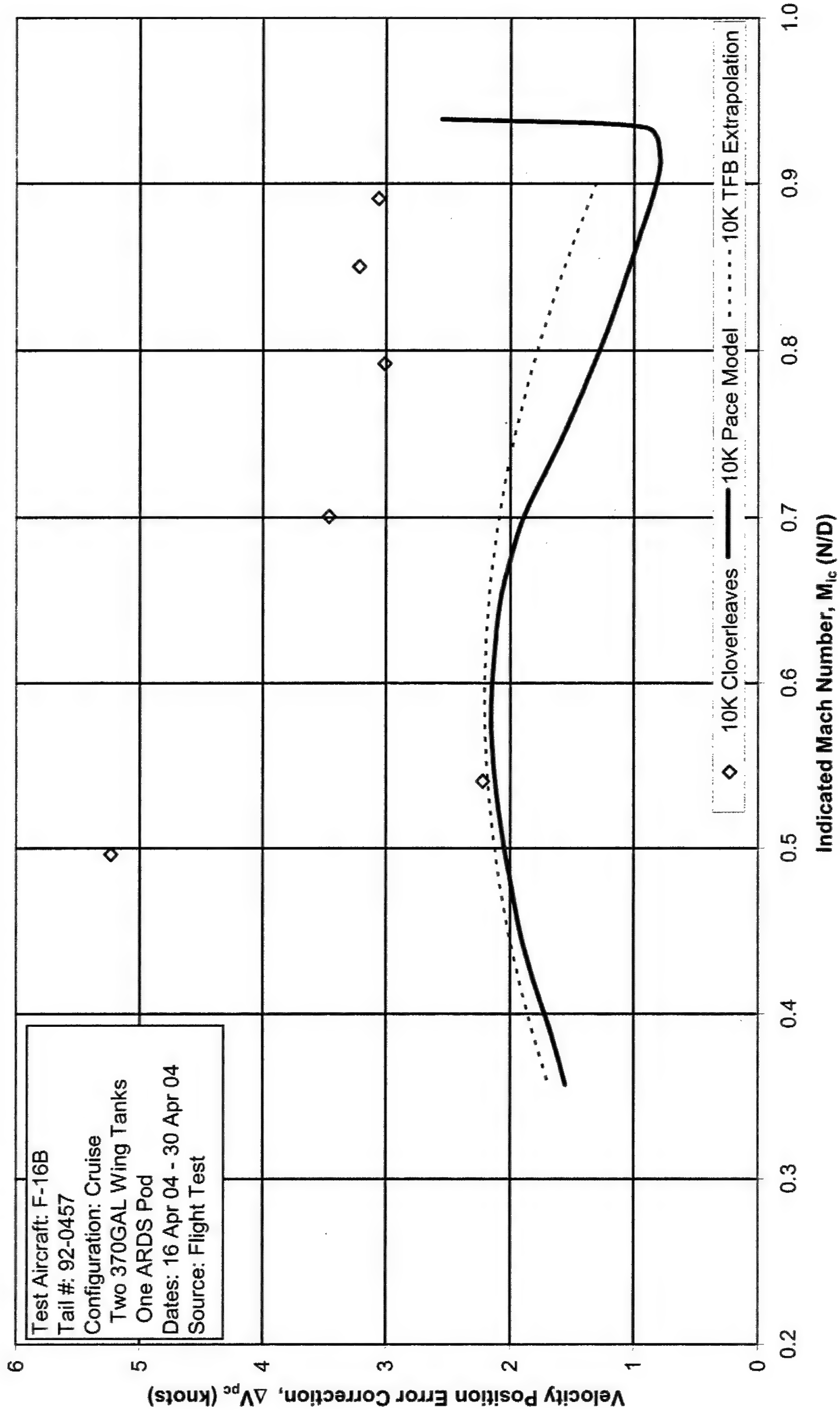


Figure 33. Airspeed Position Error Correction (20,000 ft PA Cloverleaf)

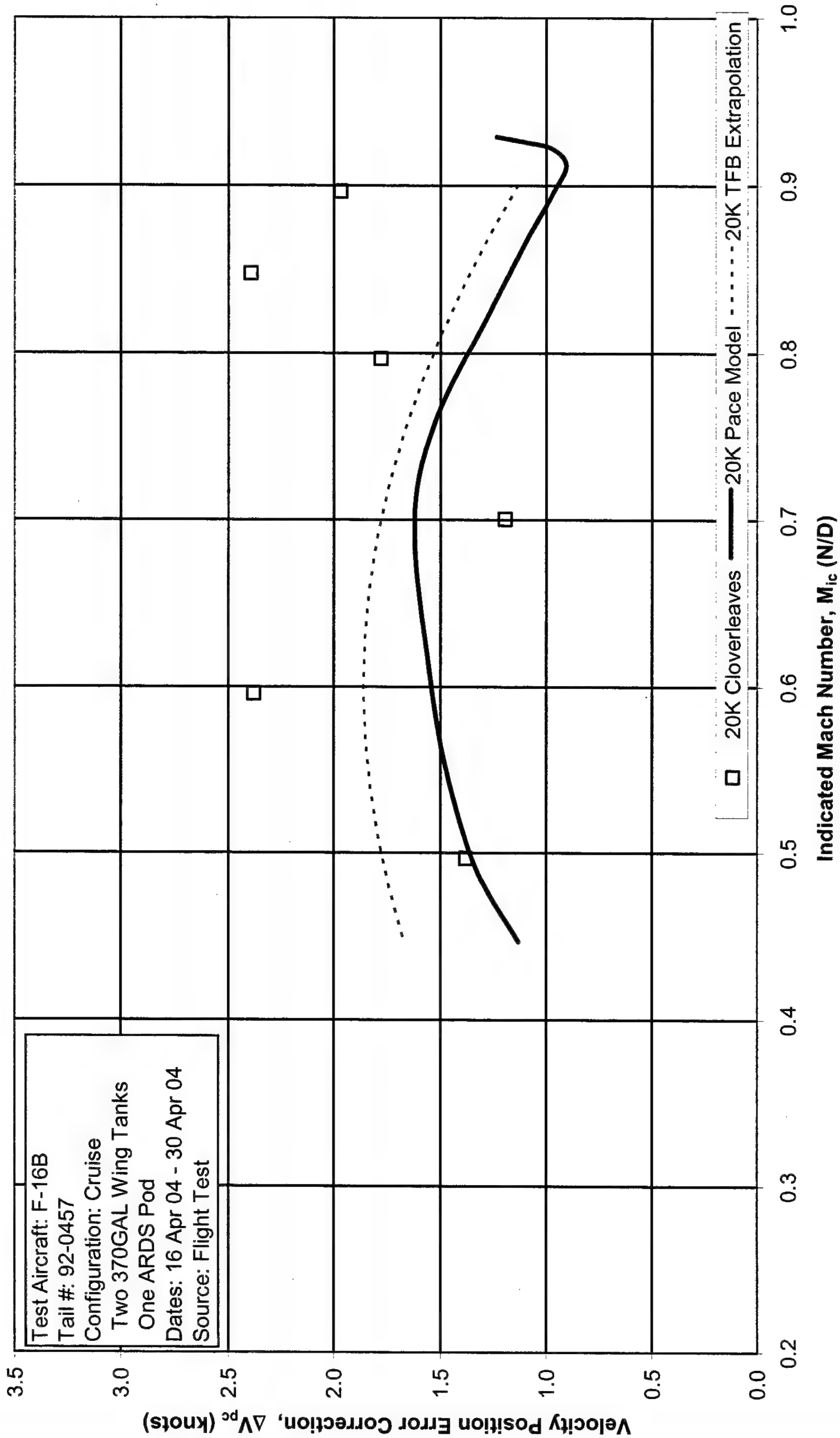


Figure 34. Airspeed Position Error Correction (30,000 ft PA Cloverleaf)

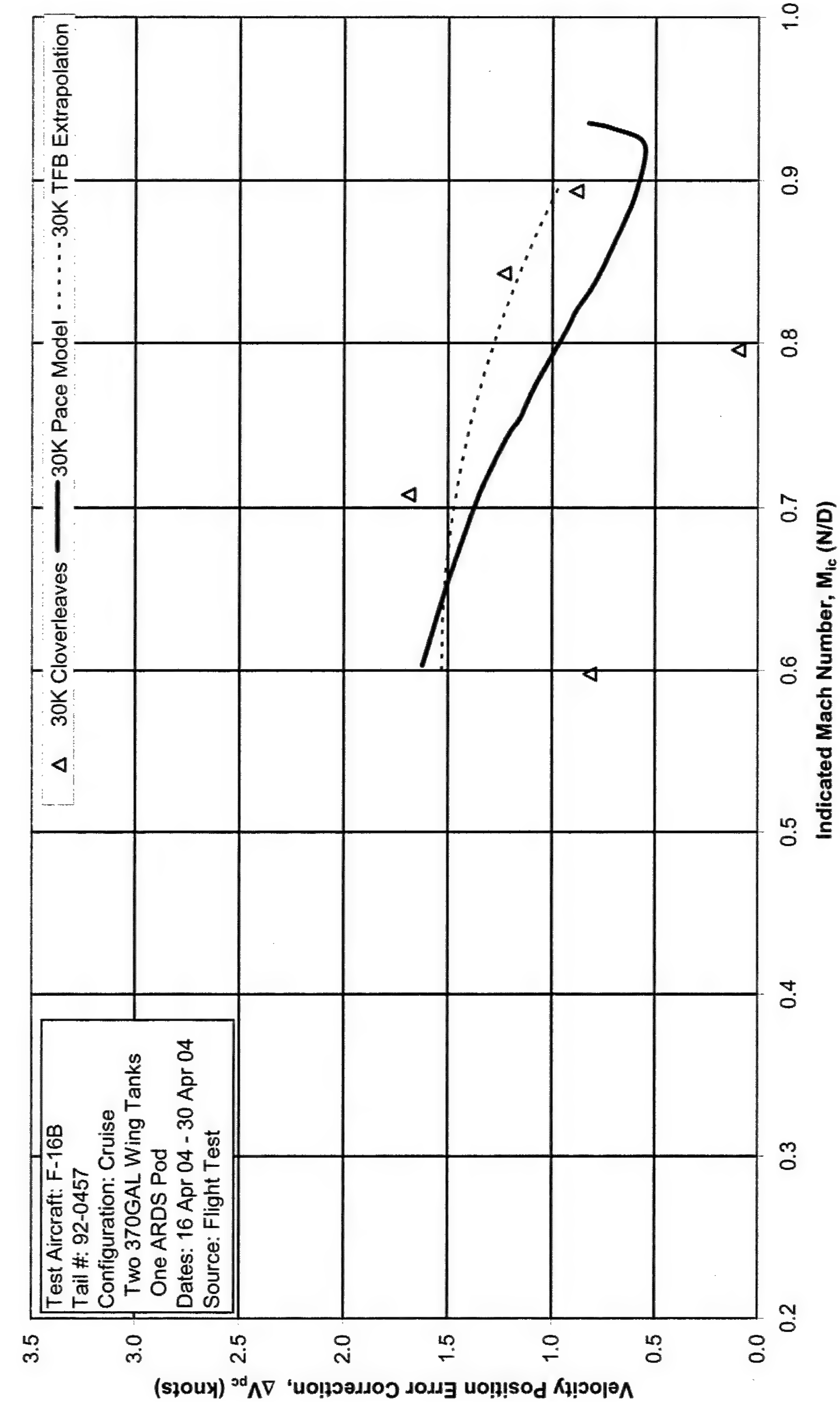


Figure 35. Airspeed Position Error Correction (35,000 ft PA Cloverleaf)

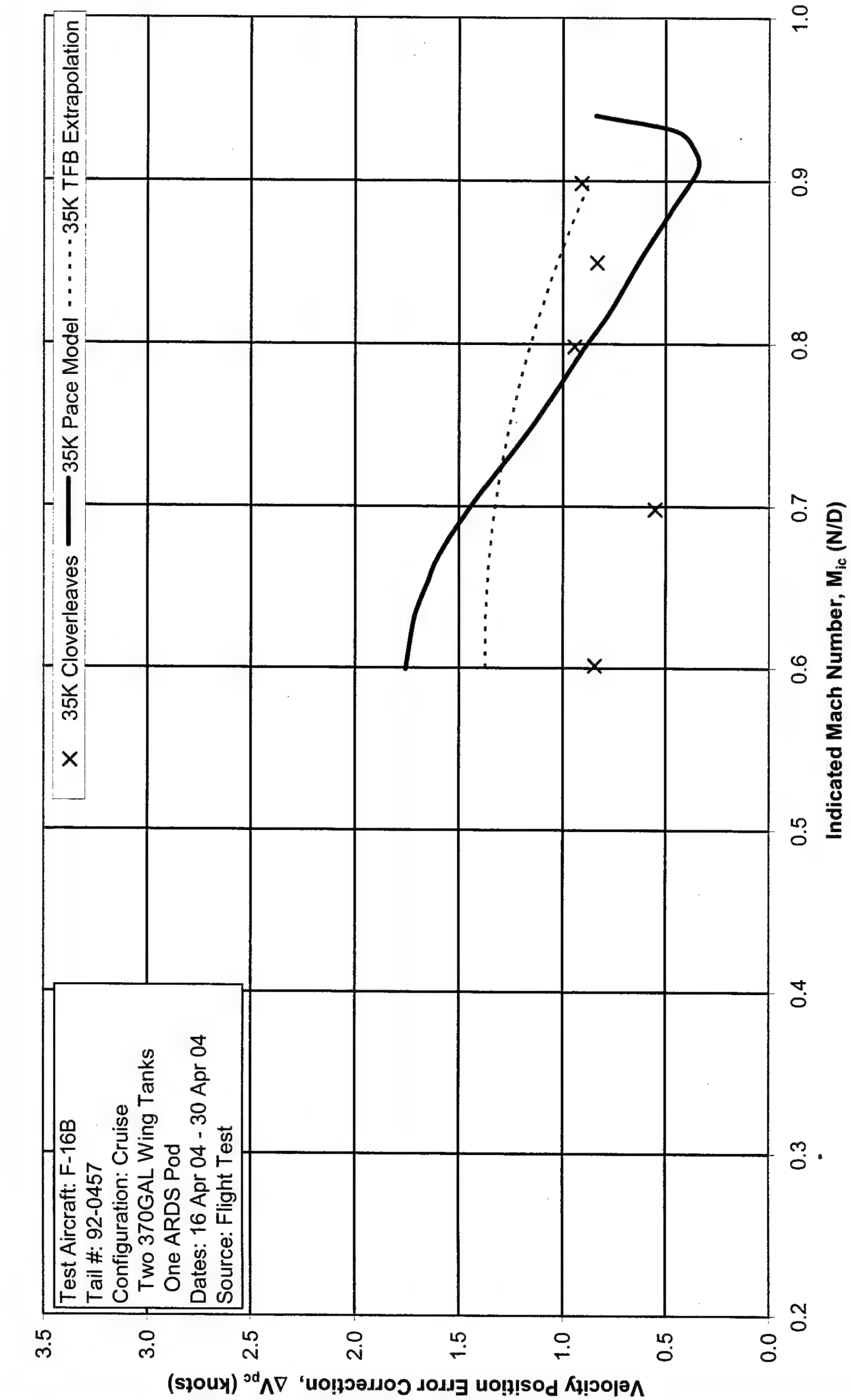


Figure 36. Airspeed Position Error Correction (10,000 ft PA Level Accel/Decel)

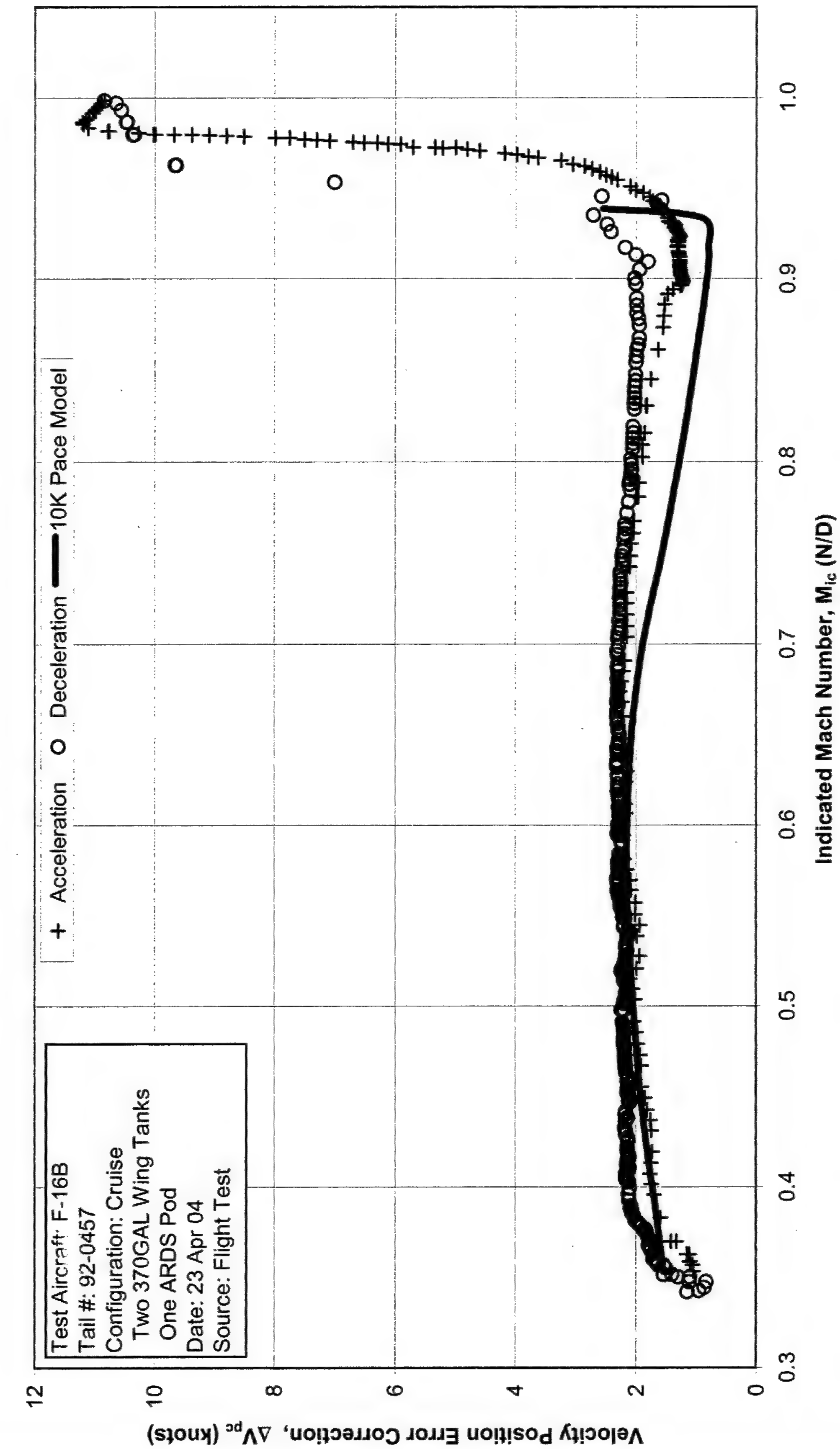


Figure 37. Airspeed Position Error Correction (20,000 ft PA Level Accel/Decel)

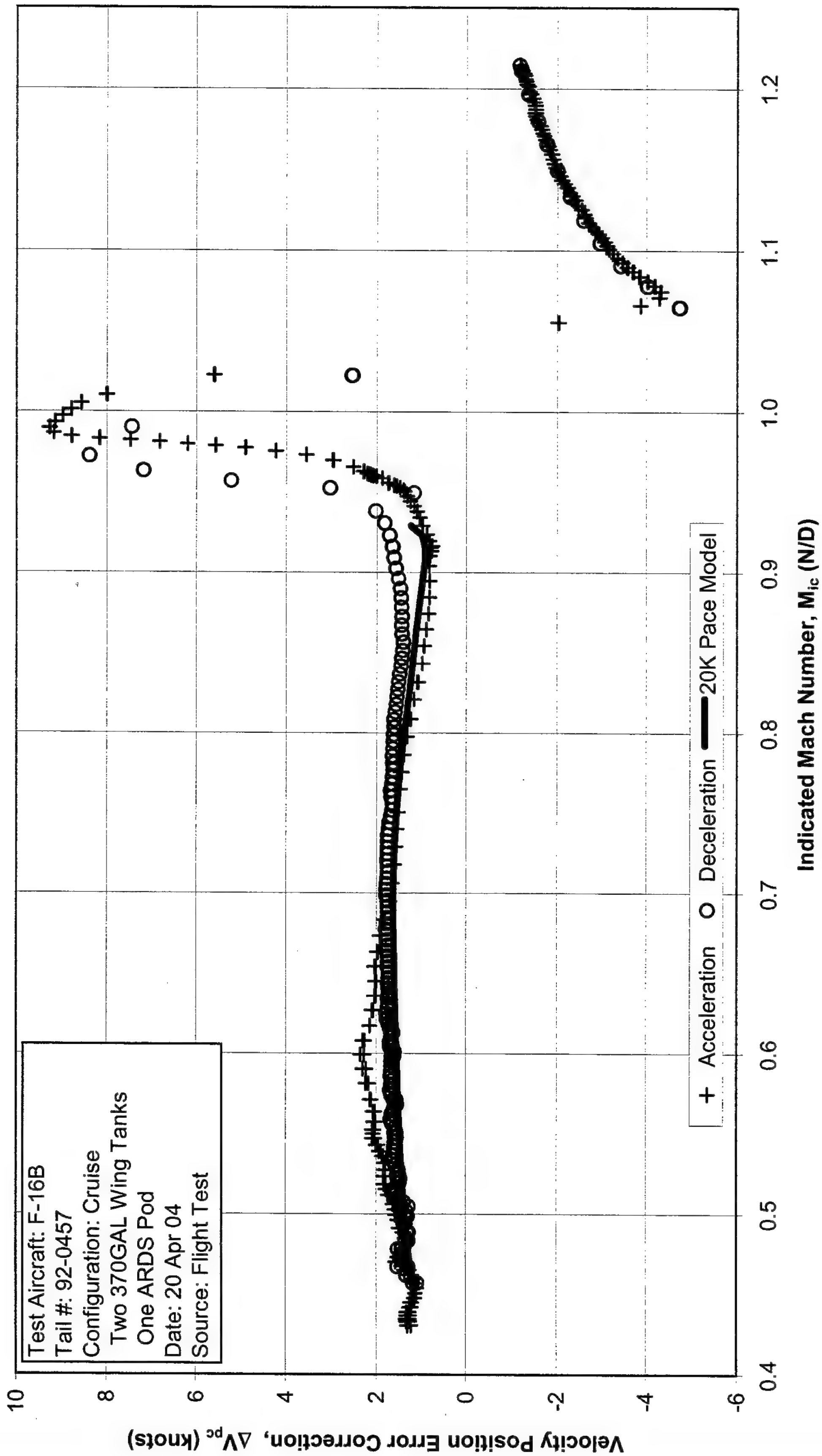


Figure 38. Airspeed Position Error Correction (30,000 ft PA Level Accel/Decel)

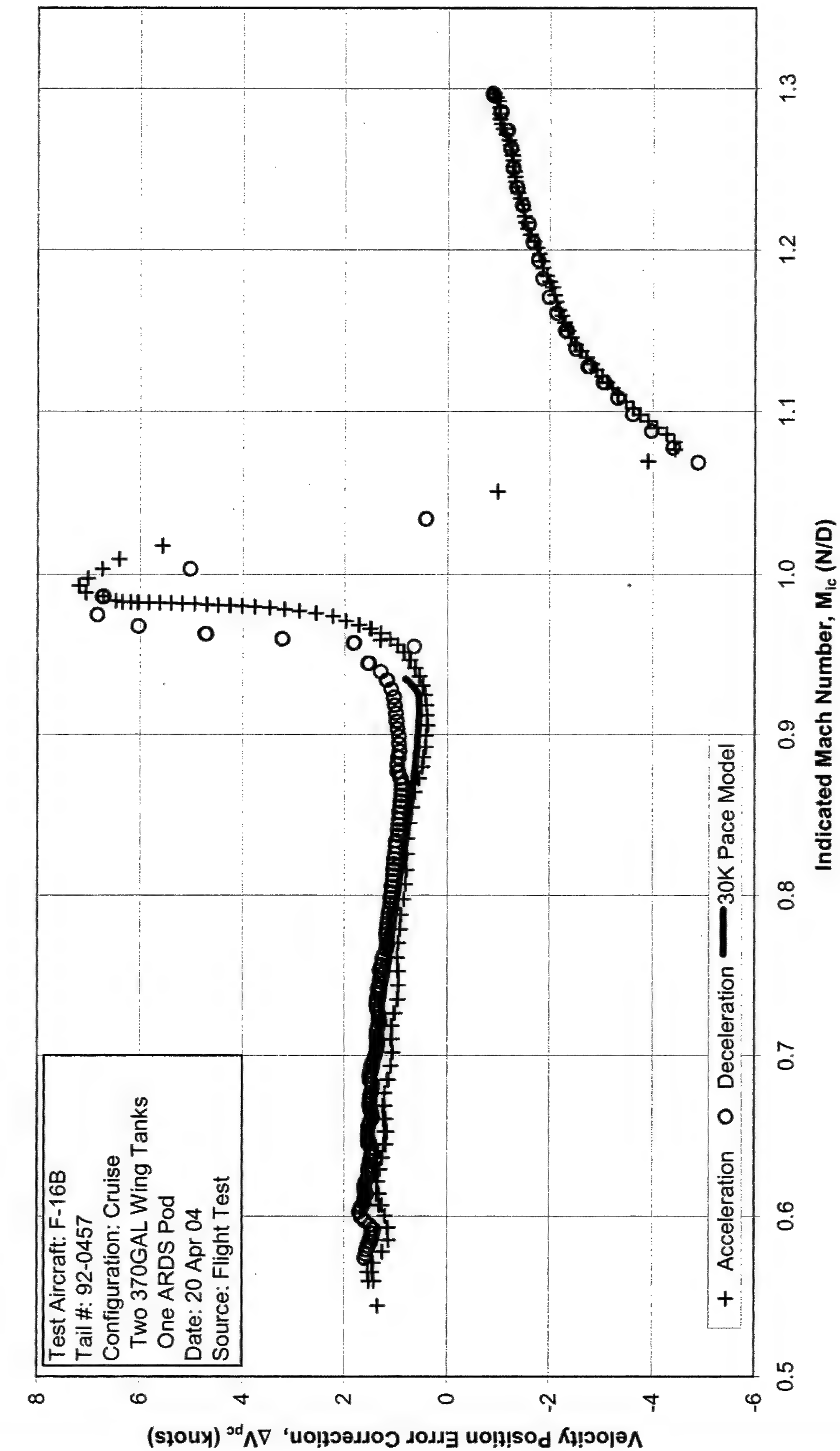


Figure 39. Airspeed Position Error Correction (35,000 ft PA Level Accel/Decel)

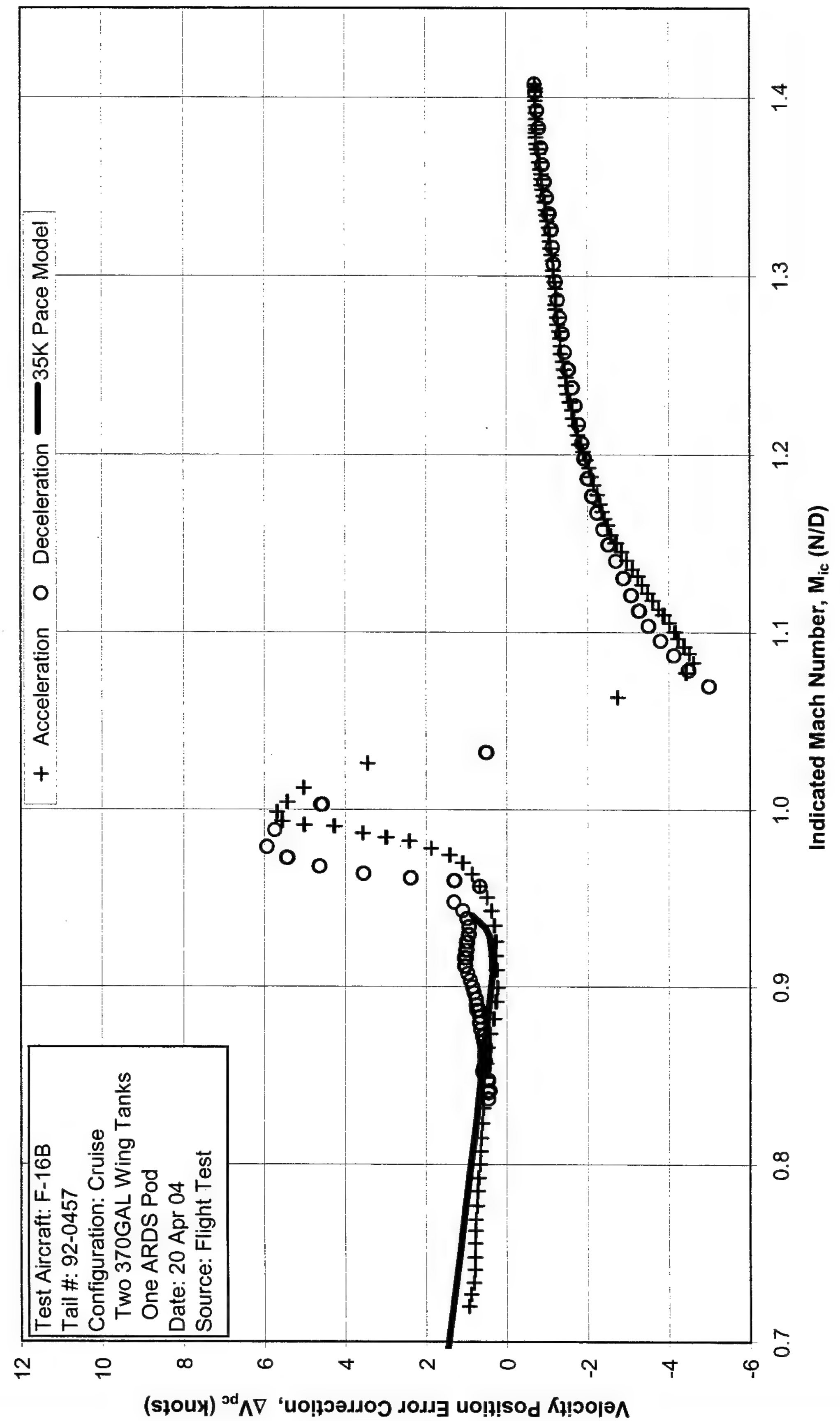


Figure 40. Airspeed Position Error Correction (40,000 ft PA Level Accel/Decel)

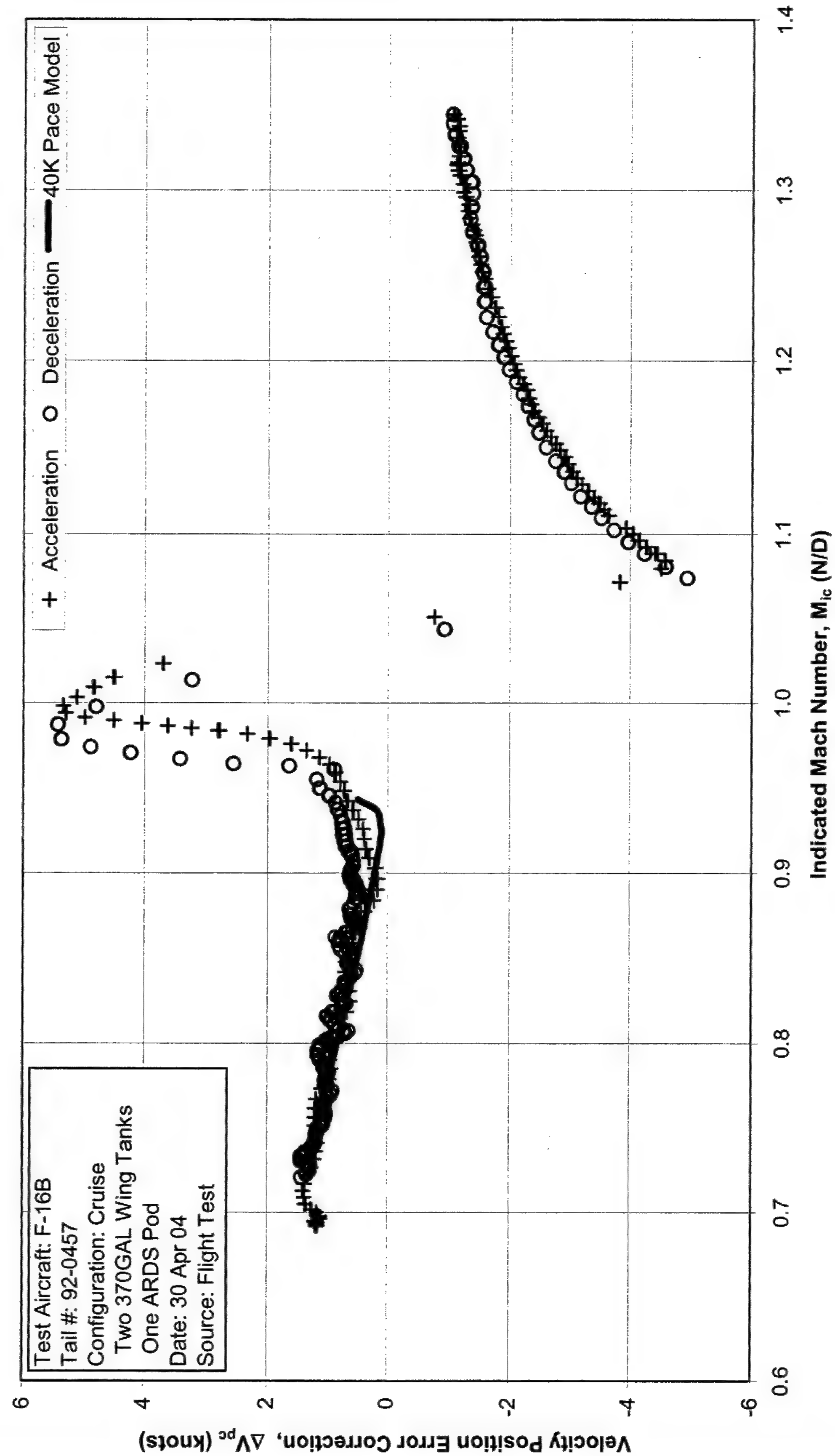


Figure 41. Mach Number Position Error Correction (Tower Fly-By)

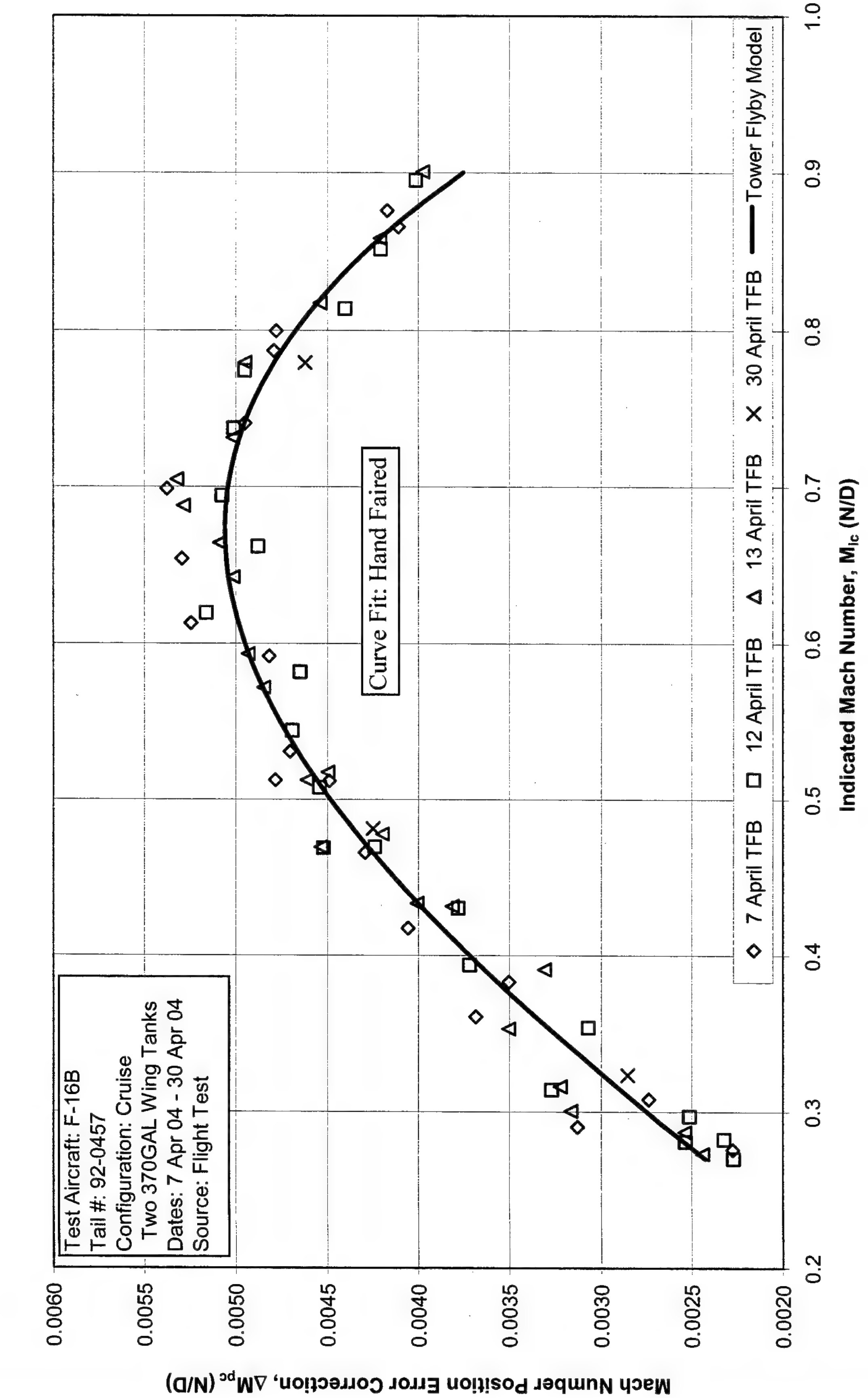


Figure 42. Mach Number Position Error Correction (10,000 ft PA Pace)

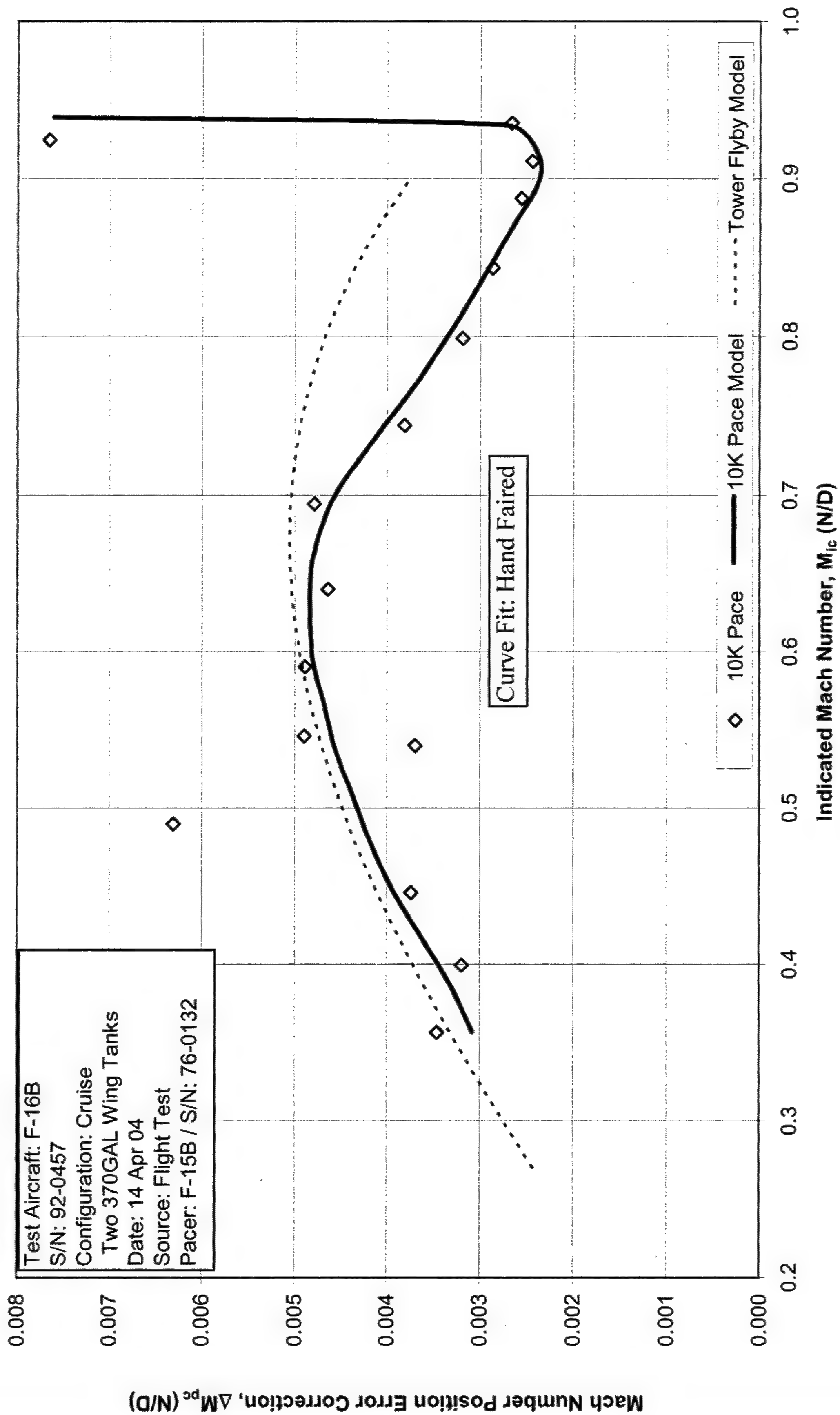


Figure 43. Mach Number Position Error Correction (20,000 ft PA Pace)

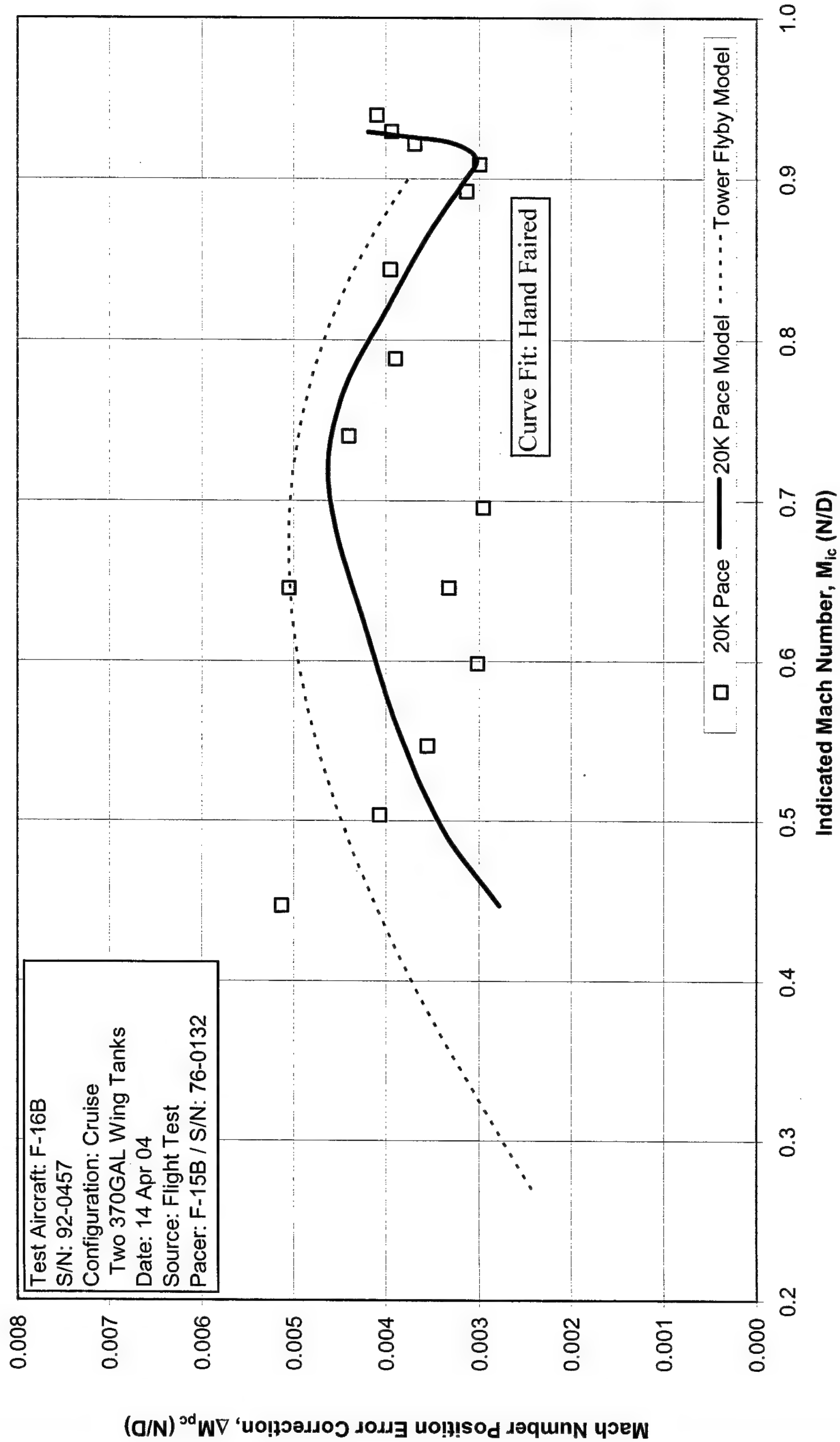


Figure 44. Mach Number Position Error Correction (30,000 ft PA Pace)

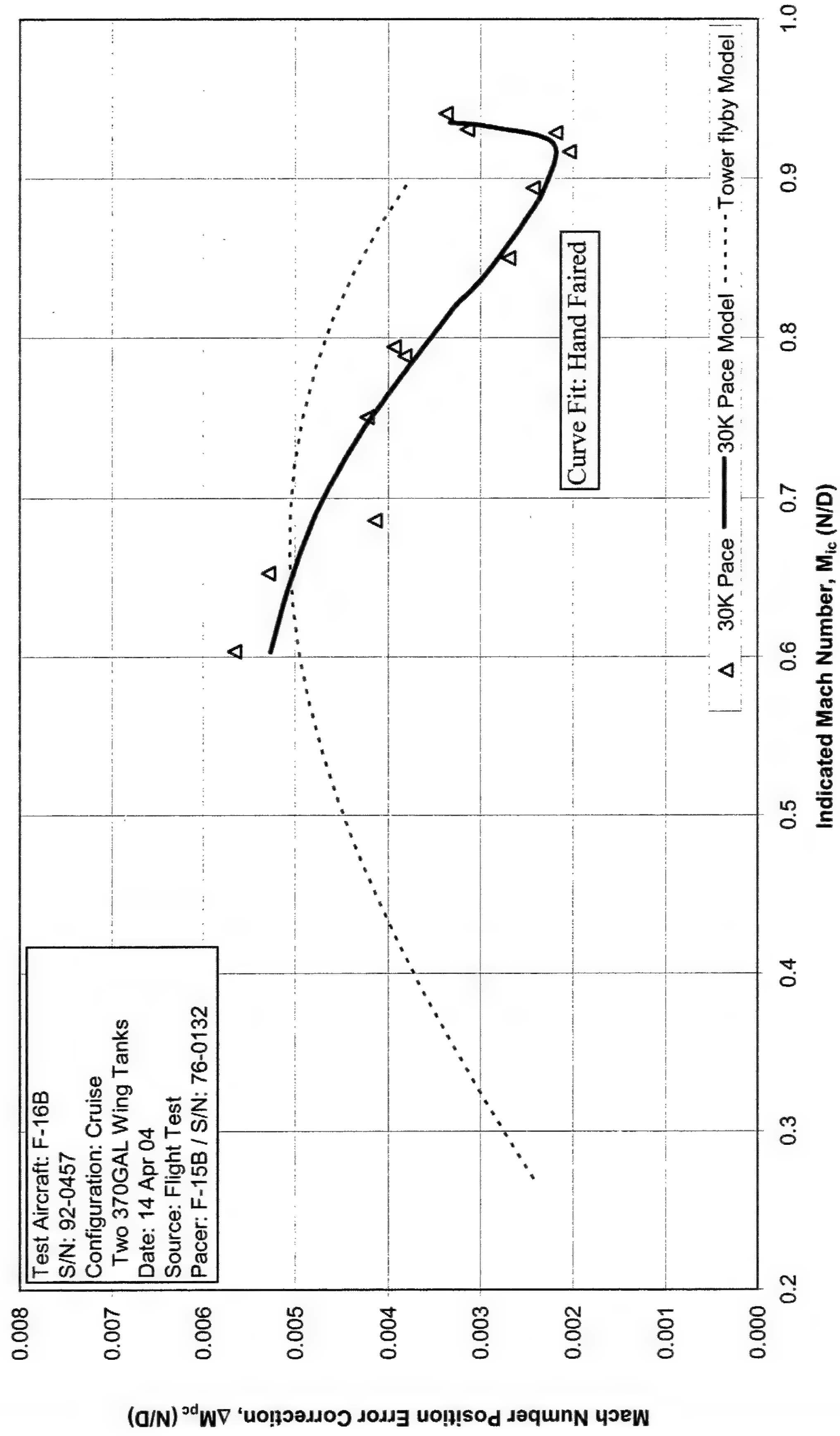


Figure 45. Mach Number Position Error Correction (35,000 ft PA Pace)

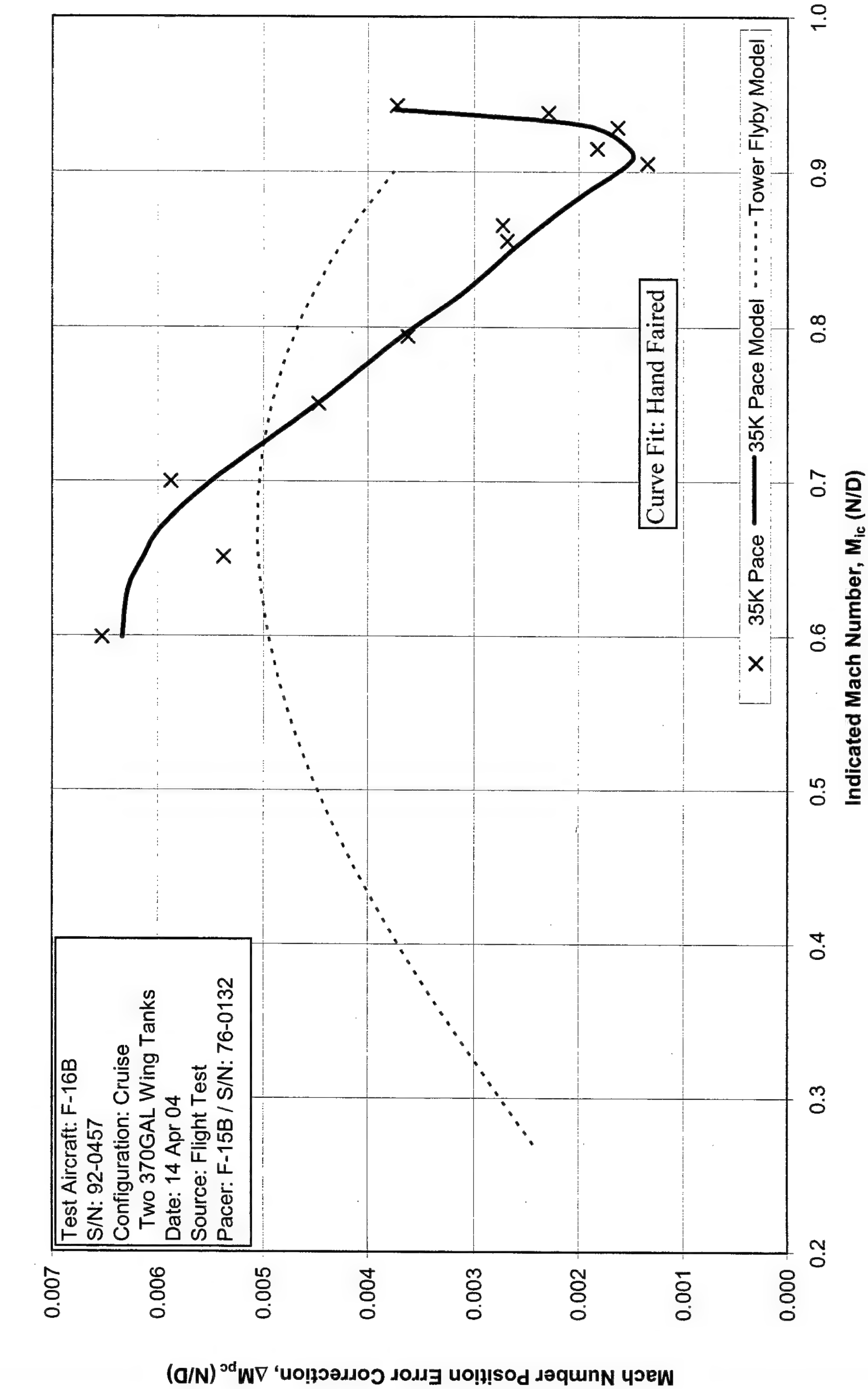
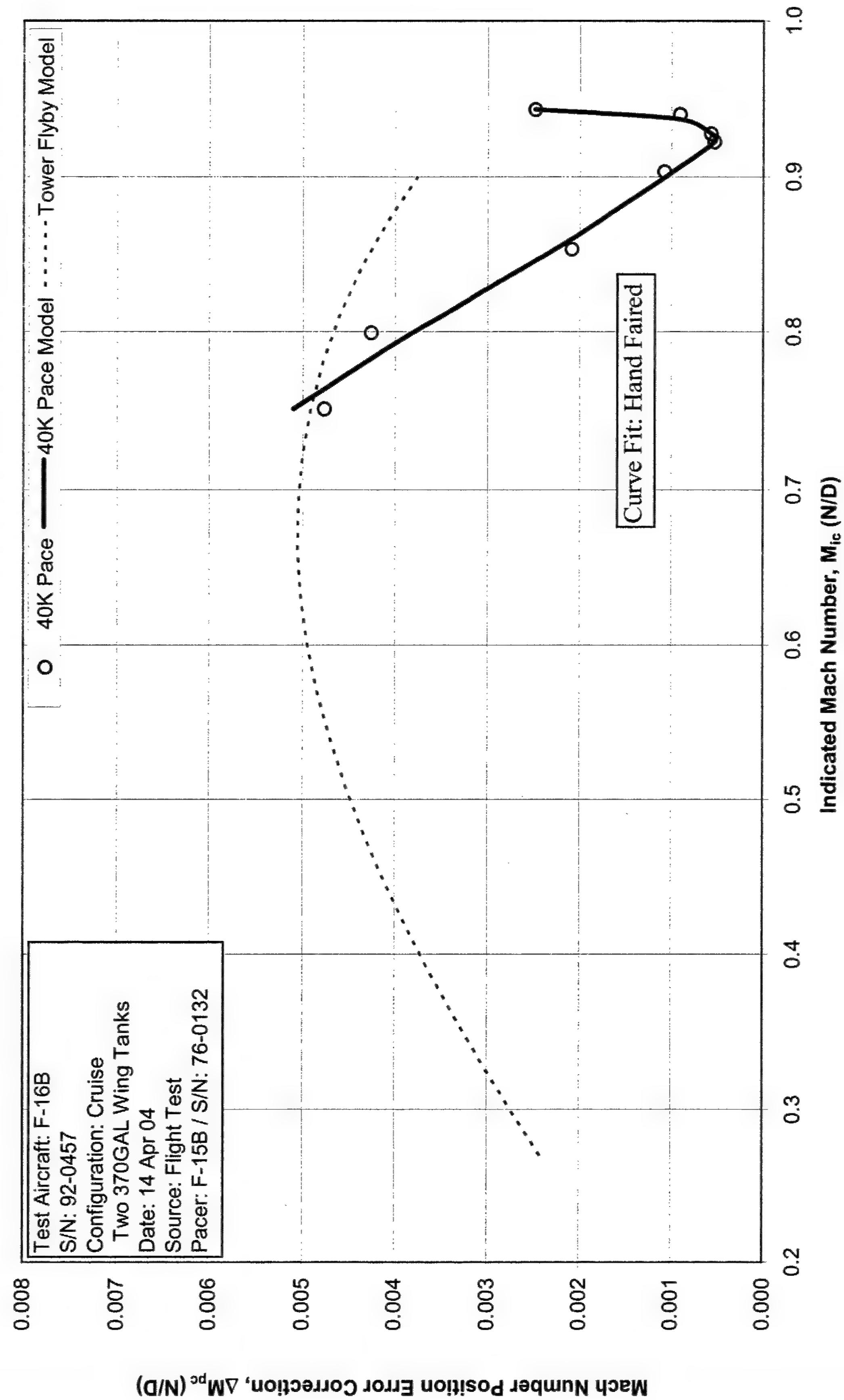


Figure 46. Mach Number Position Error Correction (40,000 ft PA Pace)



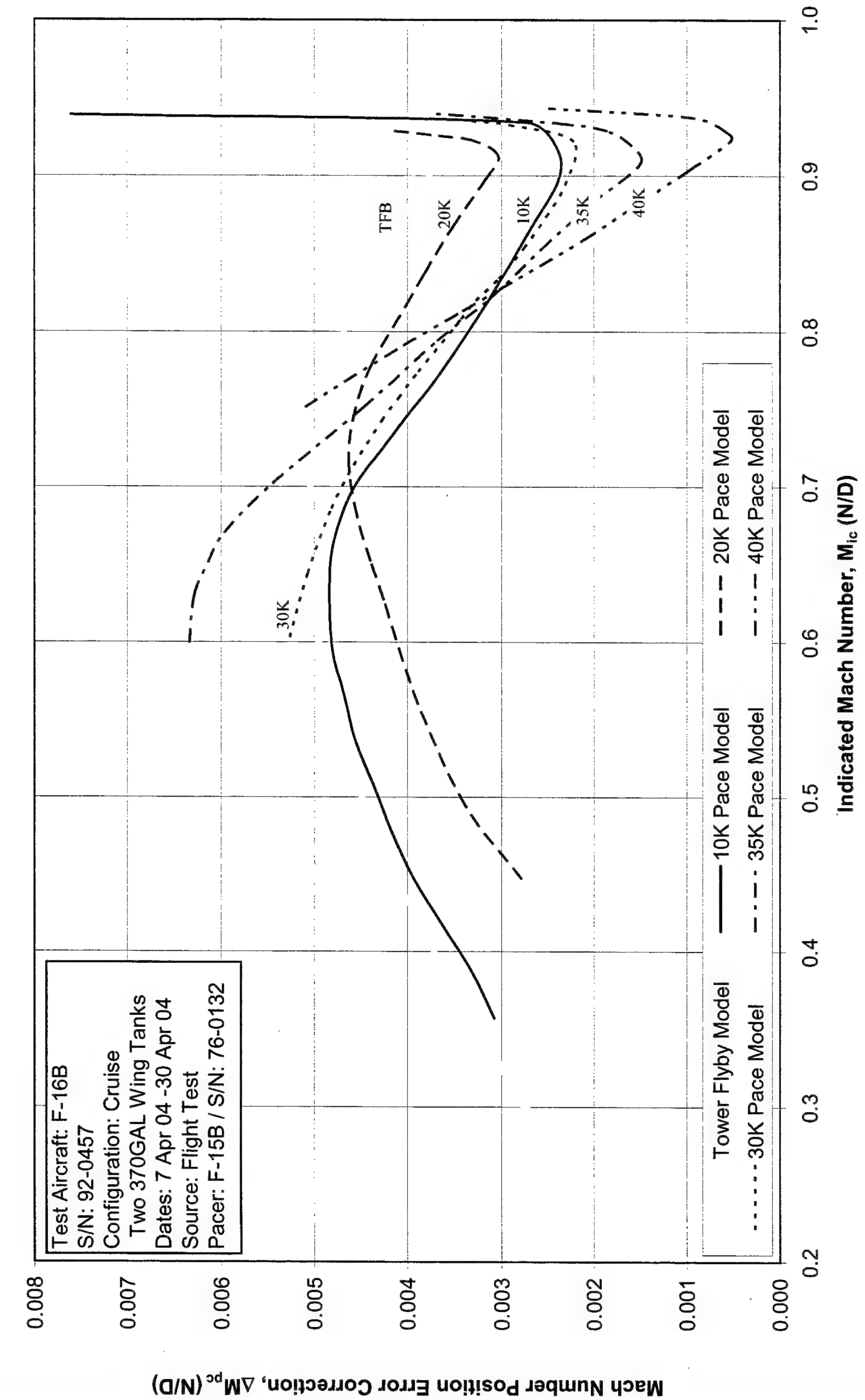


Figure 47. Mach Number Position Error Correction (Tower Fly-By & Pace)

Figure 48. Mach Number Position Error Correction (10,000 ft PA Cloverleaf)

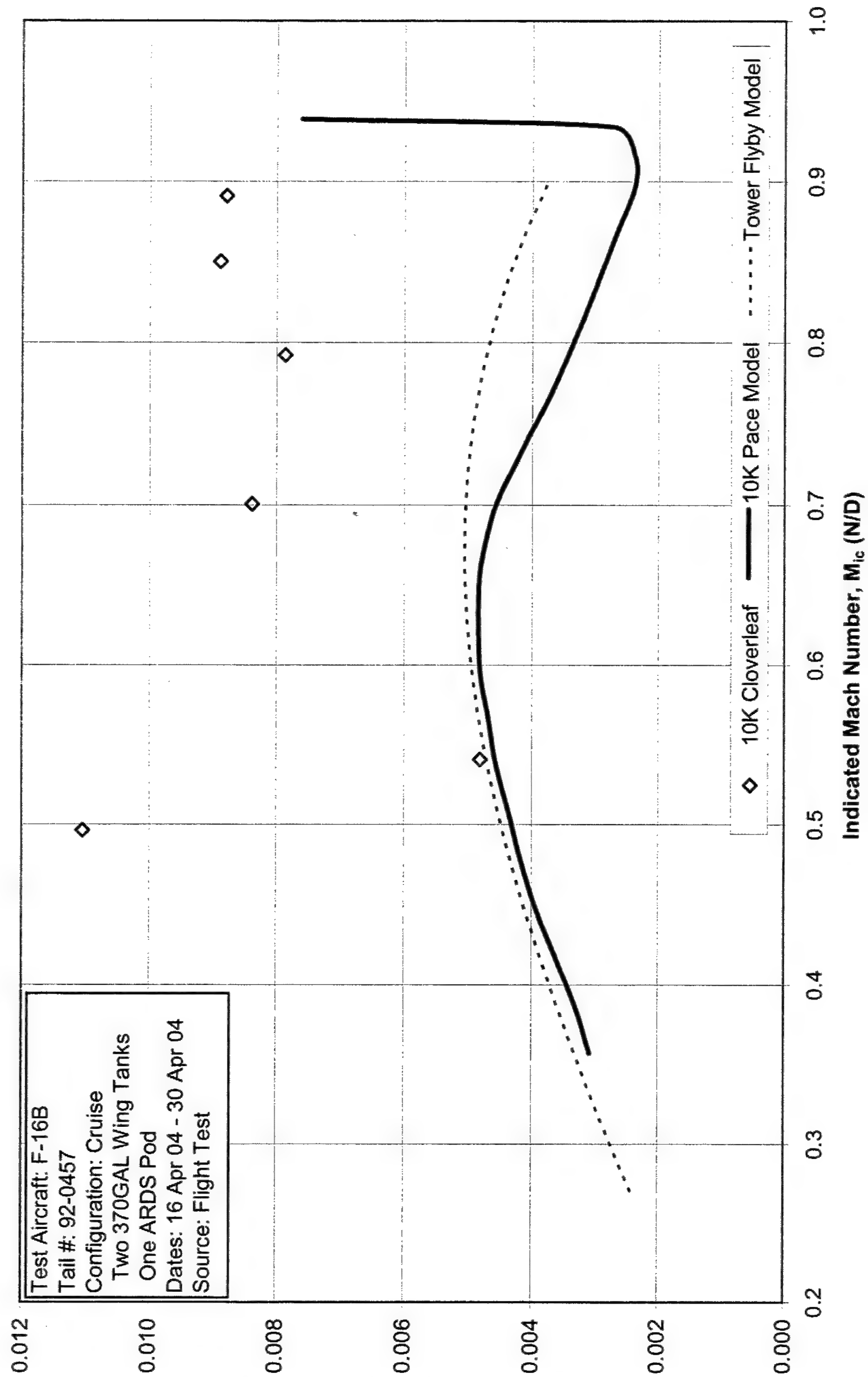


Figure 49. Mach Number Position Error Correction (20,000 ft PA Cloverleaf)

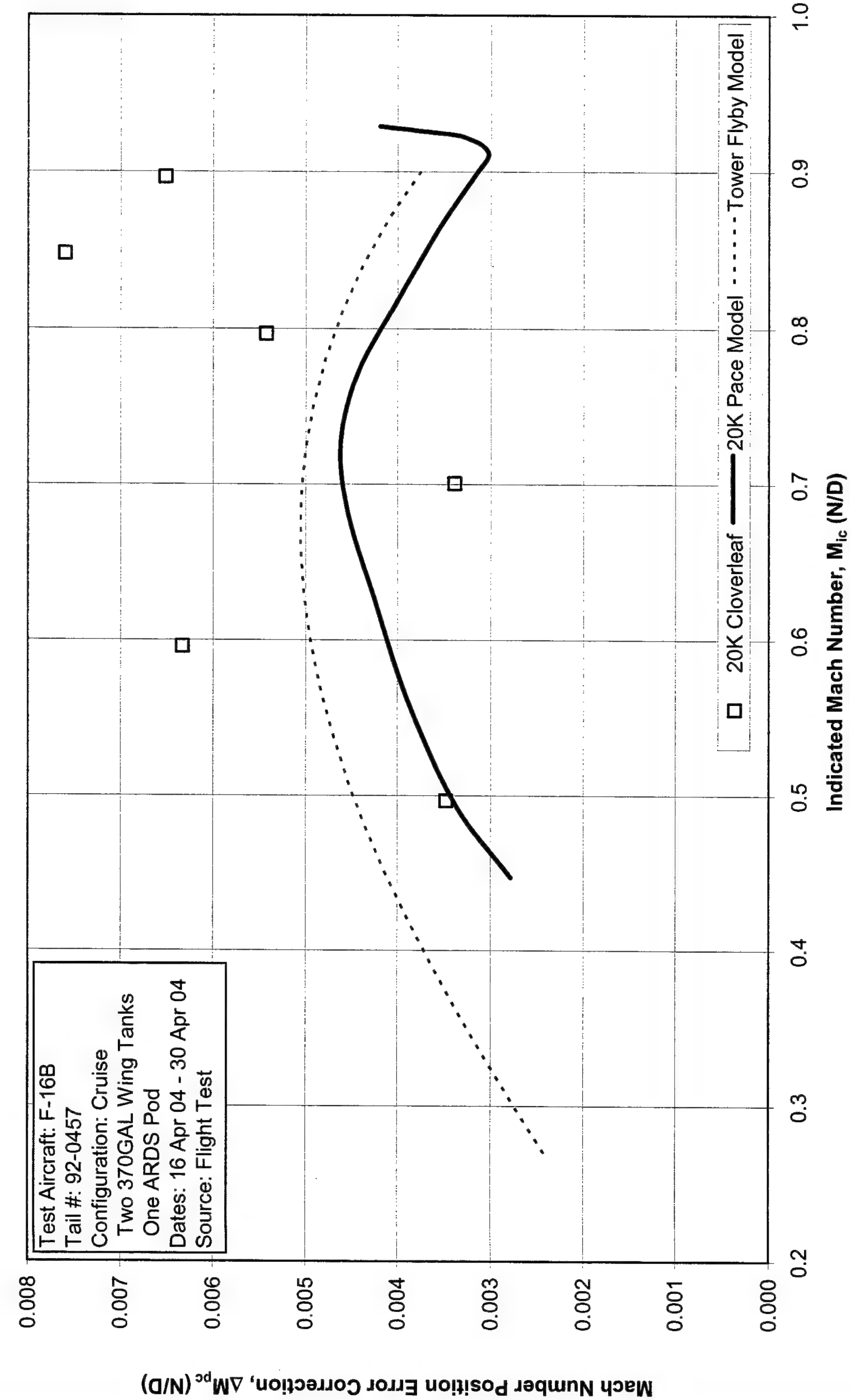


Figure 50. Mach Number Position Error Correction (30,000 ft PA Cloverleaf)

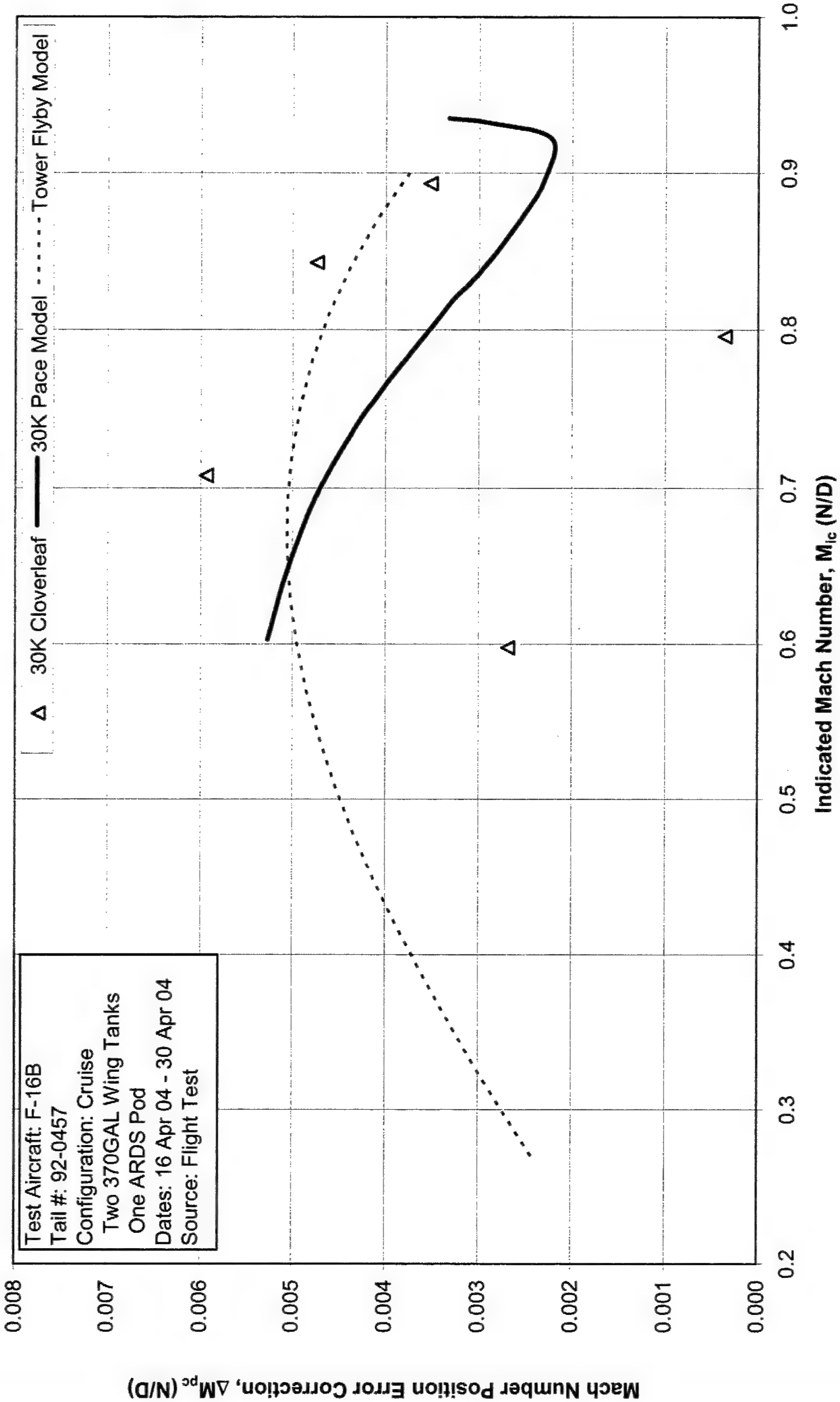


Figure 51. Mach Number Position Error Correction (35,000 ft PA Cloverleaf)

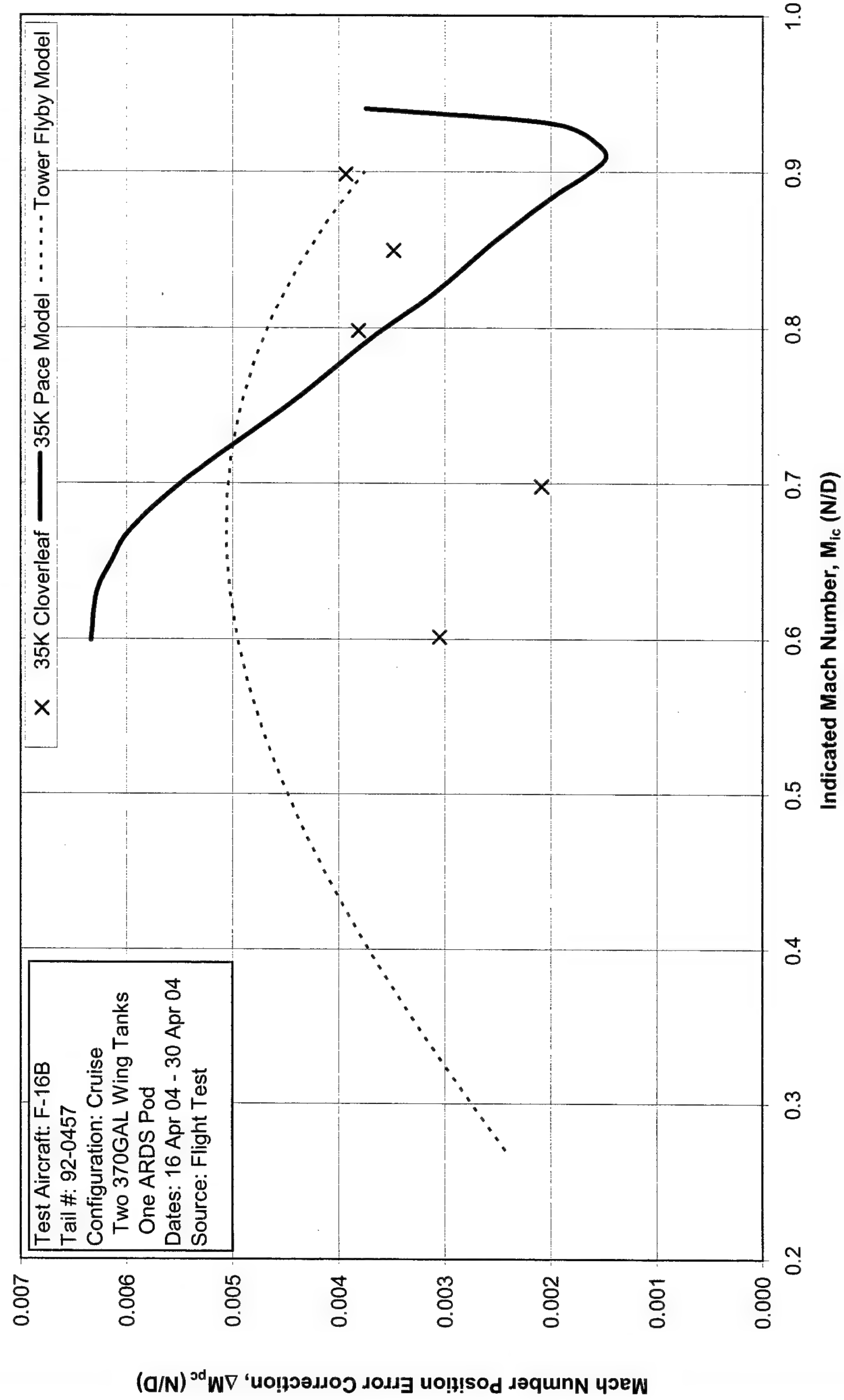


Figure 52. Mach Number Position Error Correction (10,000 ft PA Level Accel/Decel)

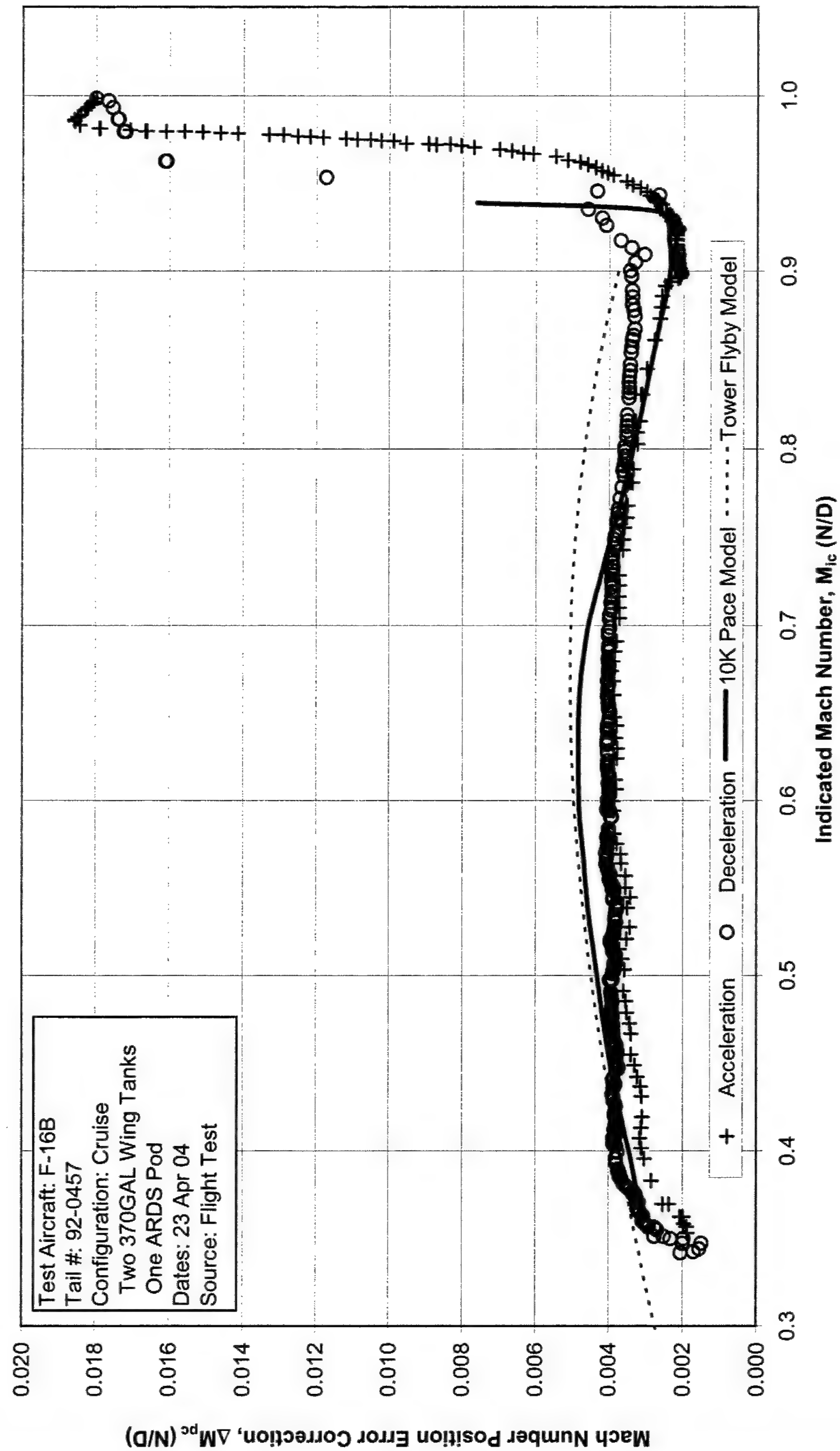


Figure 53. Mach Number Position Error Correction (20,000 ft PA Level Accel/Decel)

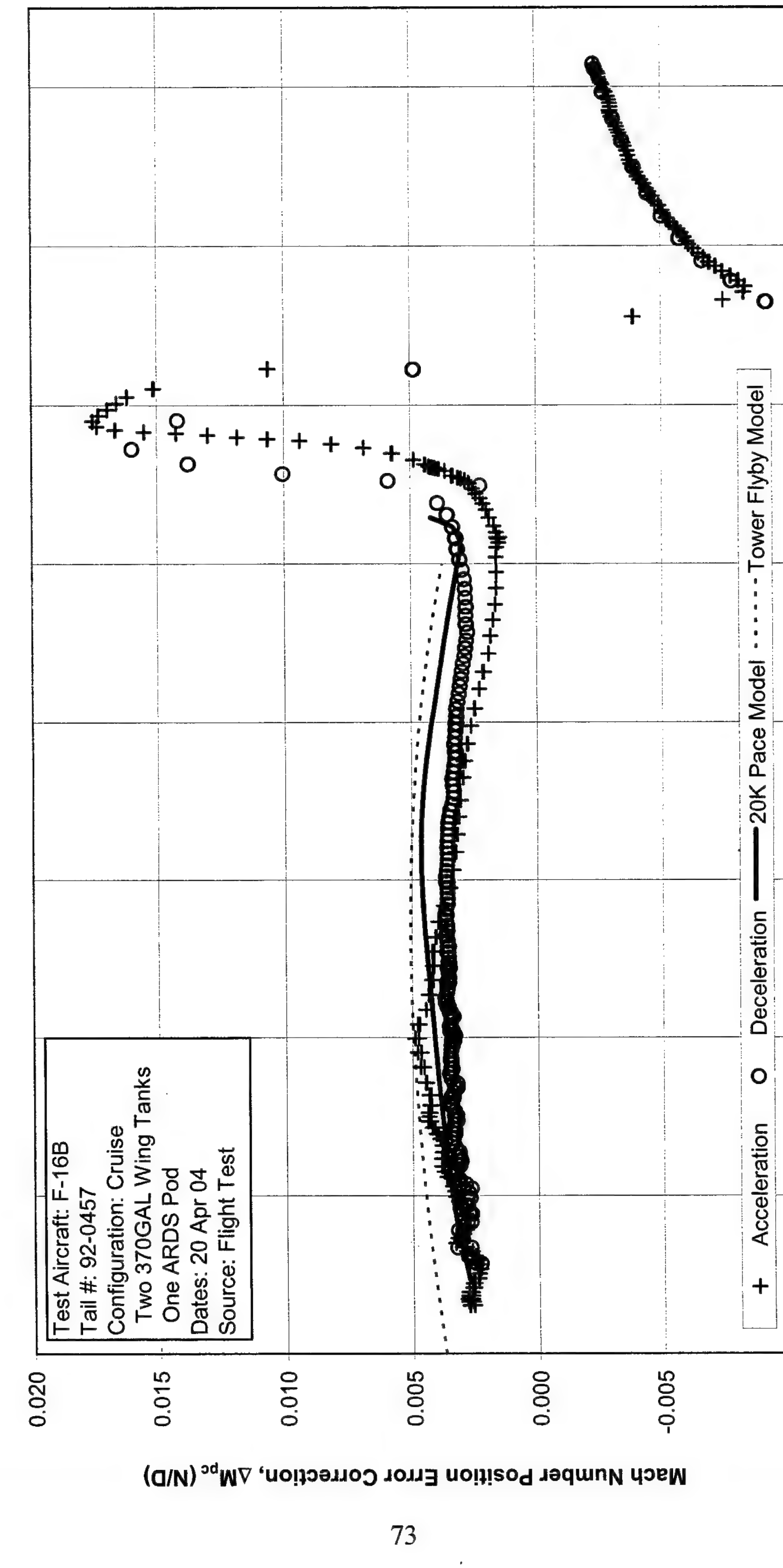


Figure 54. Mach Number Position Error Correction (30,000 ft PA Level Accel/Decel)

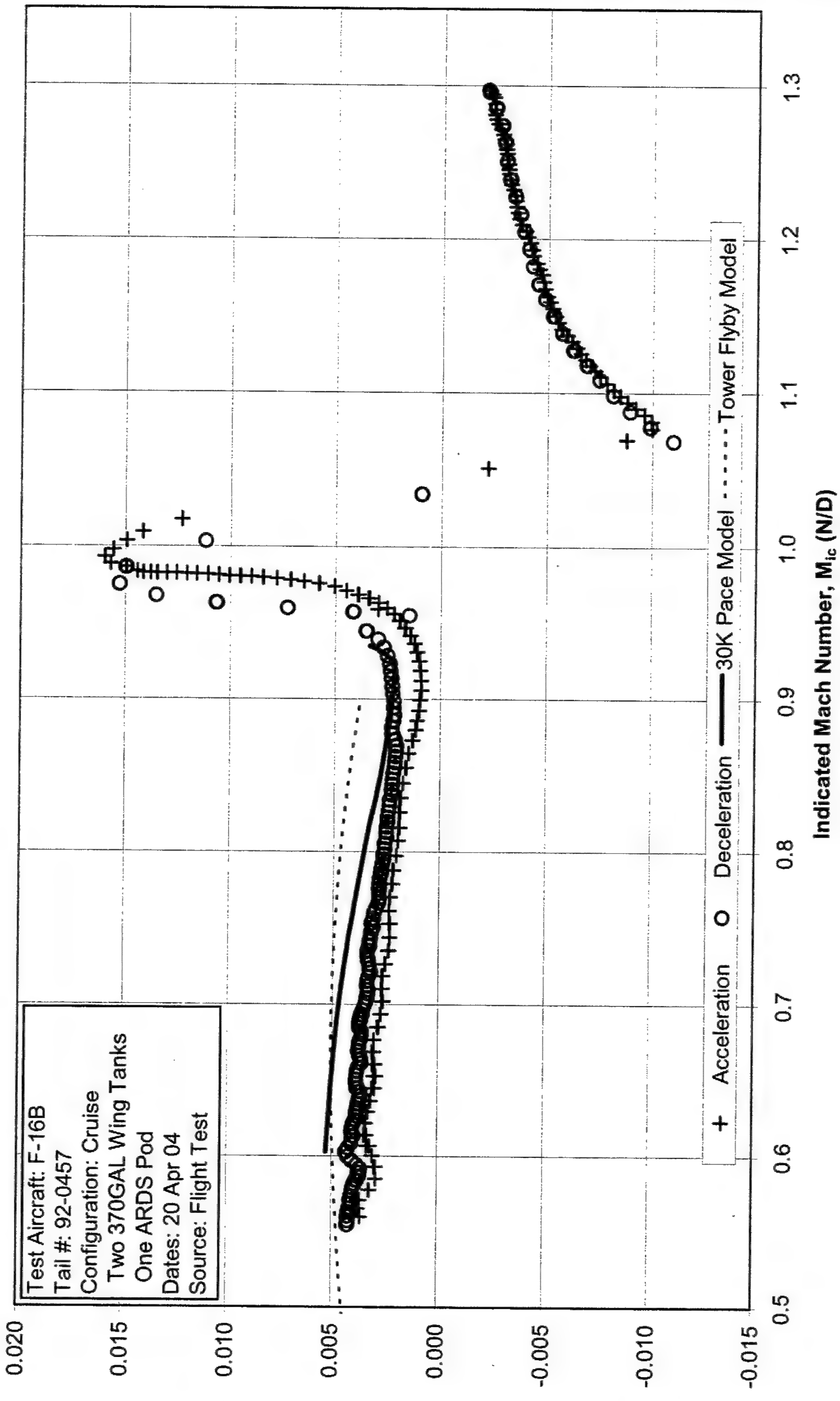


Figure 55. Mach Number Position Error Correction (35,000 ft PA Level Accel/Decel)

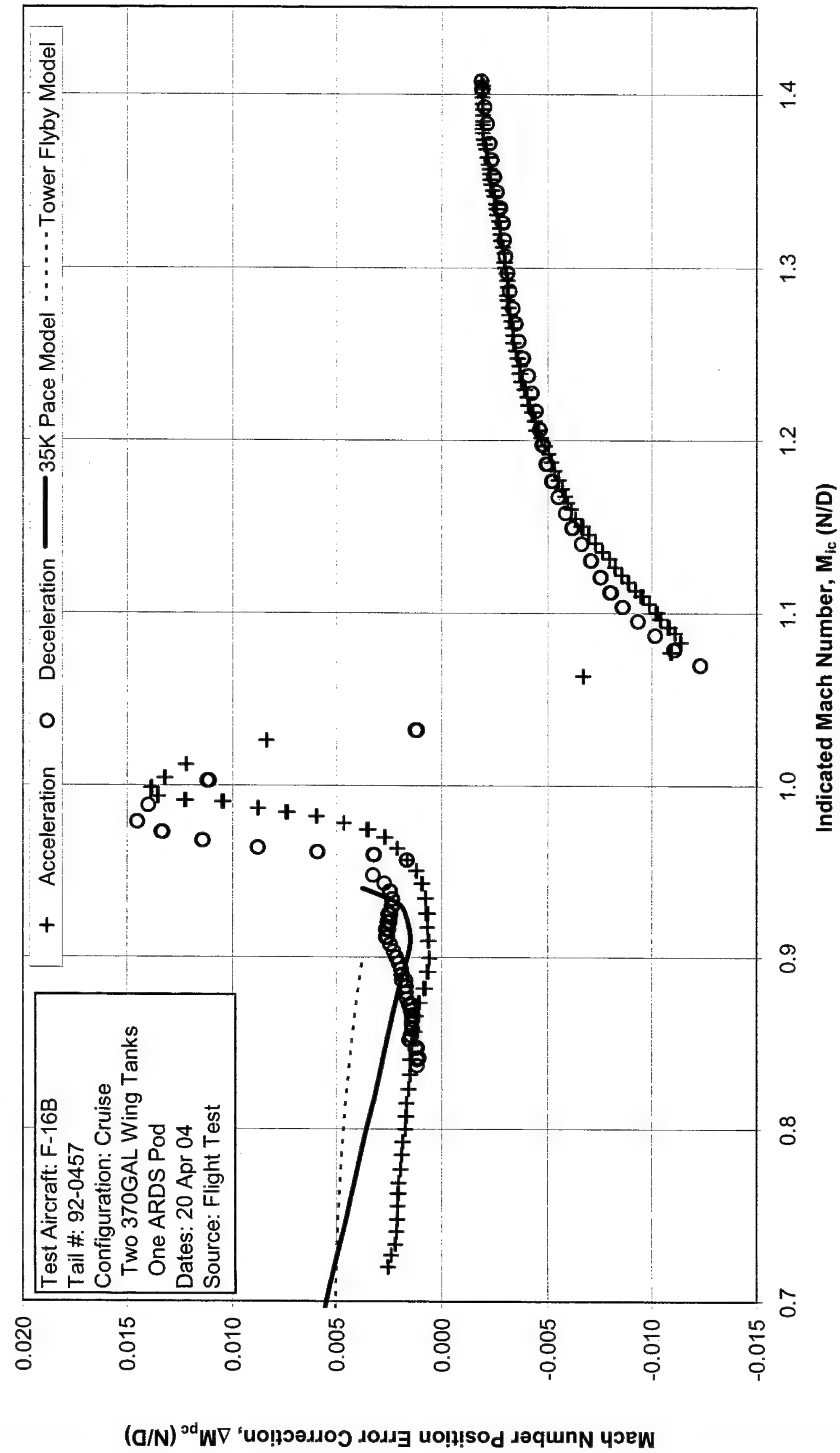


Figure 56. Mach Number Position Error Correction (40,000 ft PA Level Accel/Decel)

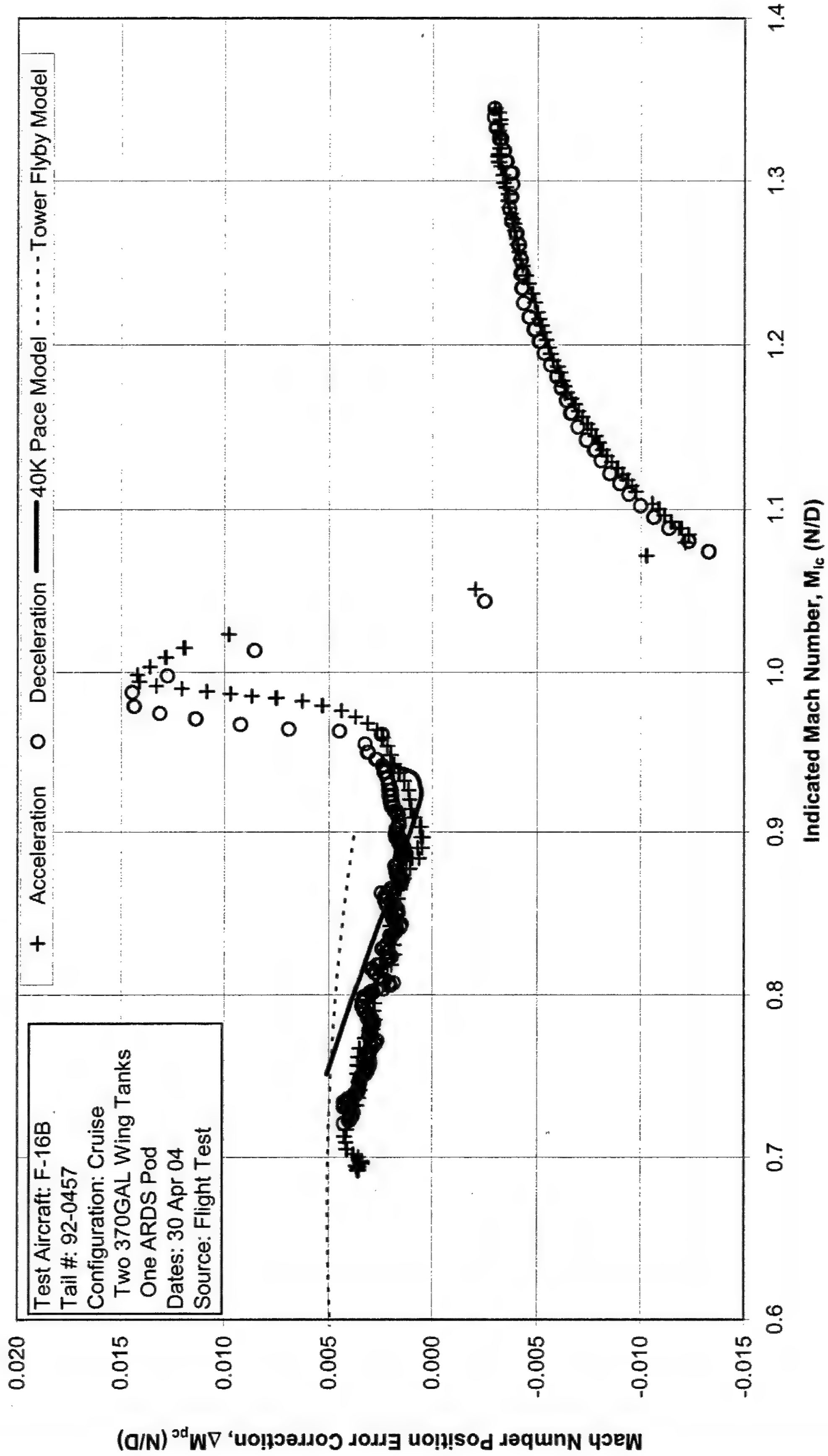


Figure 57. Mach Number Position Error Correction (10,000 ft Constant Airspeed Turn)

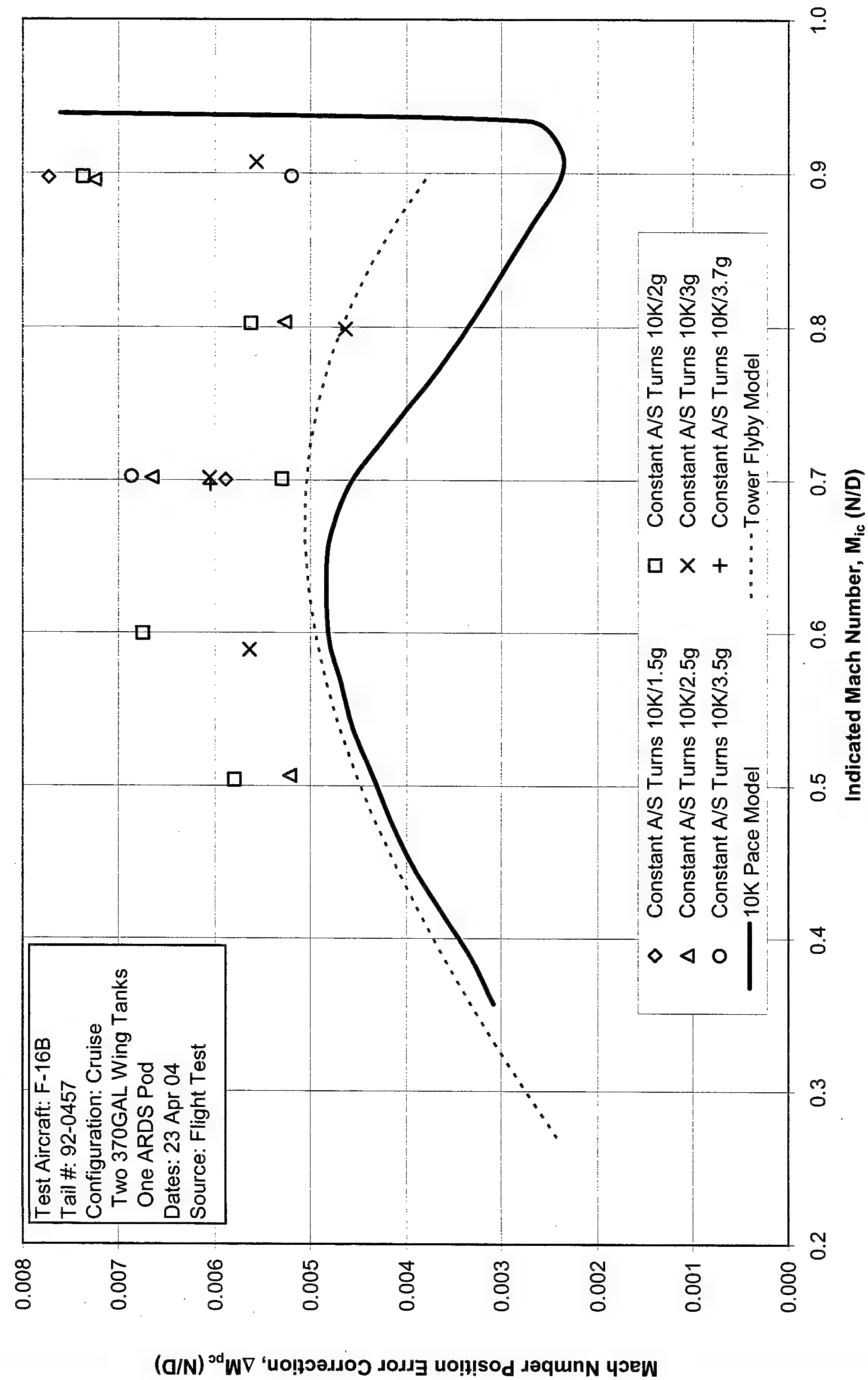
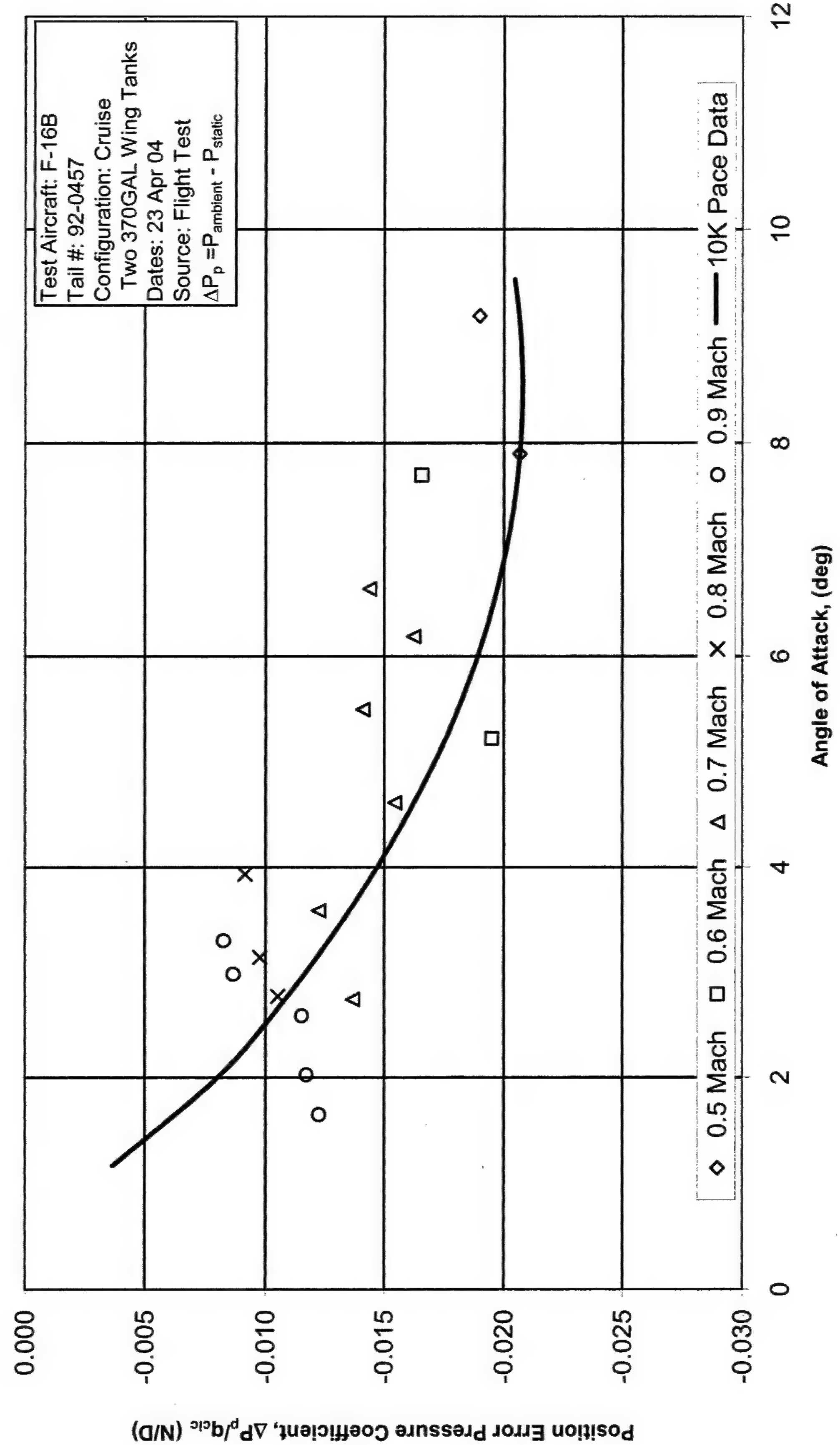


Figure 58. Position Error Pressure Coefficient Angle of Attack Effects



Note: 10K Pace Data were collected in 1G level flight

Figure 59. Altitude Position Error Correction Angle of Attack Effects

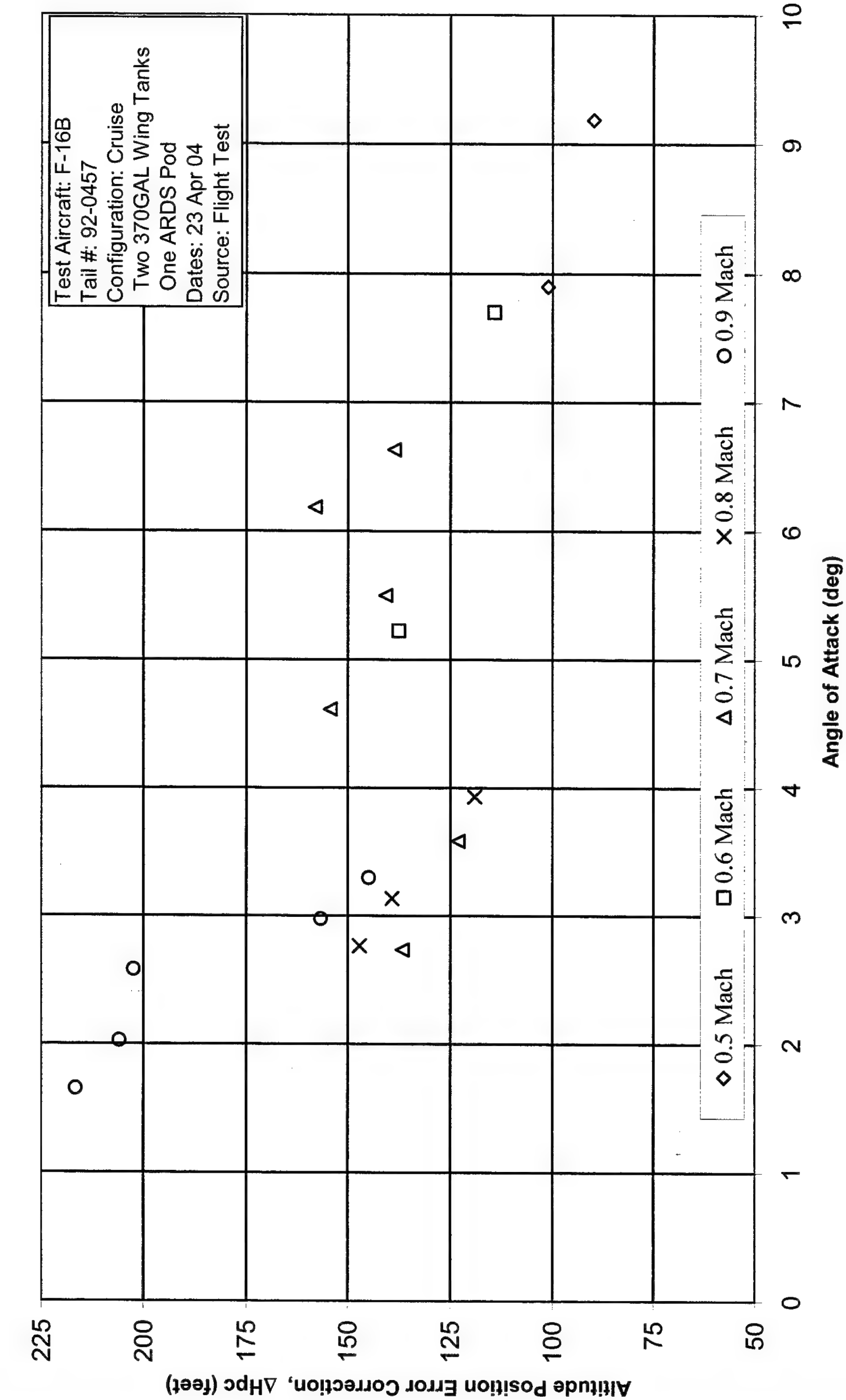


Figure 60. Mach Number Position Error Correction Angle of Attack Effects

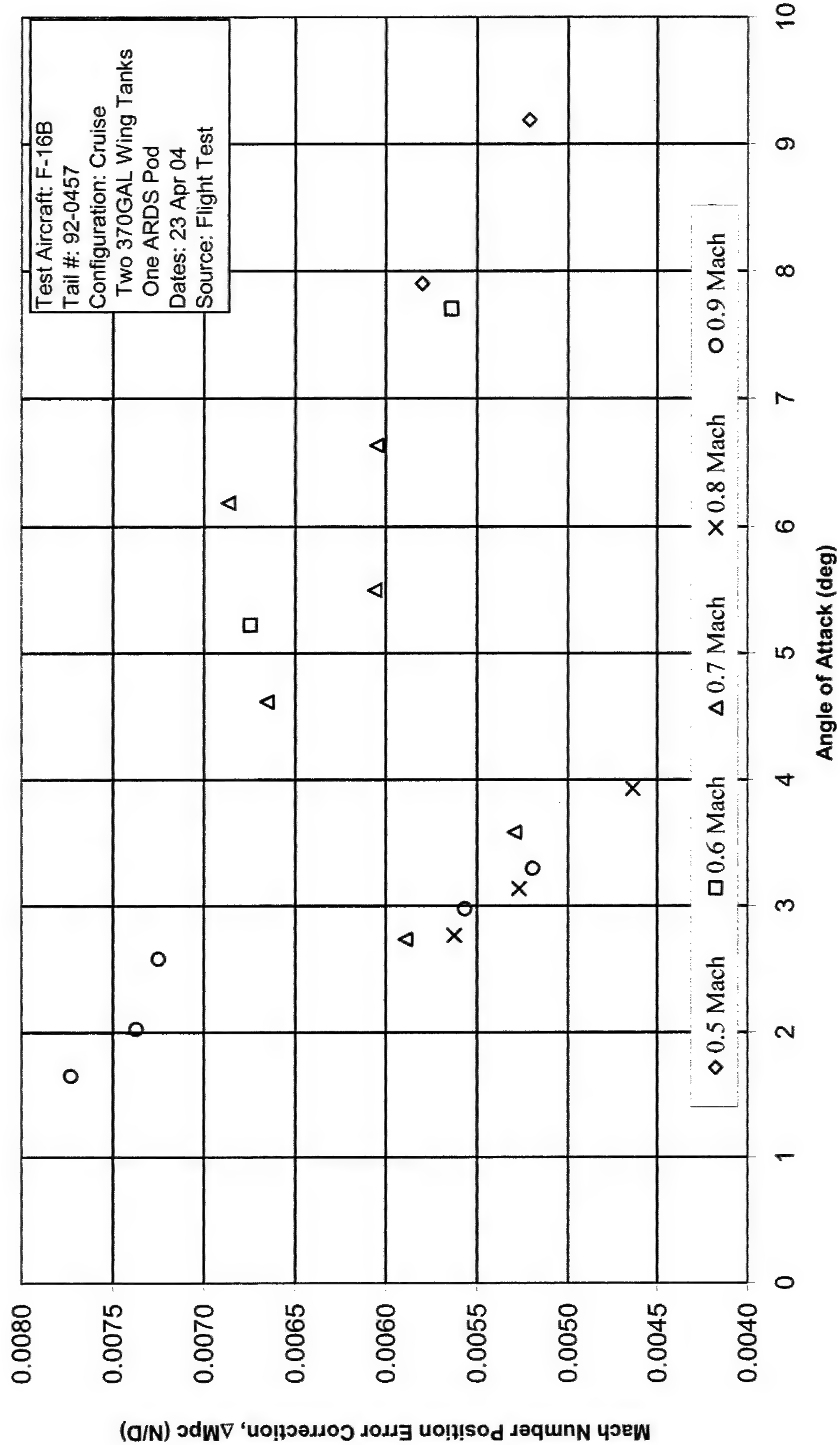


Figure 61. Total Air Temperature Probe Recovery Factor (Tower Fly-By & Pace)

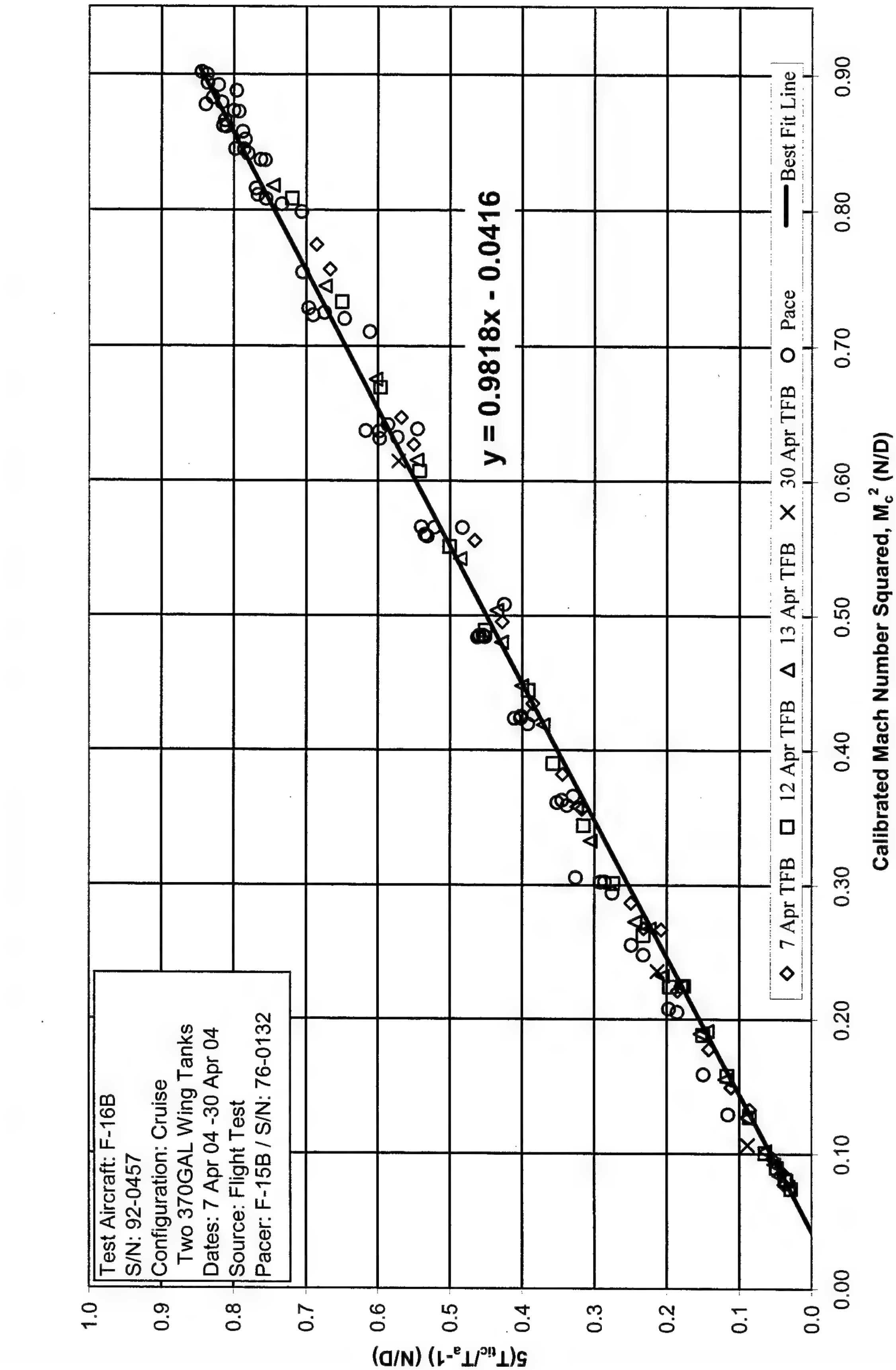


Figure 62. Total Air Temperature Probe Recovery Factor (10,000 ft PA Level Accel/Decel)

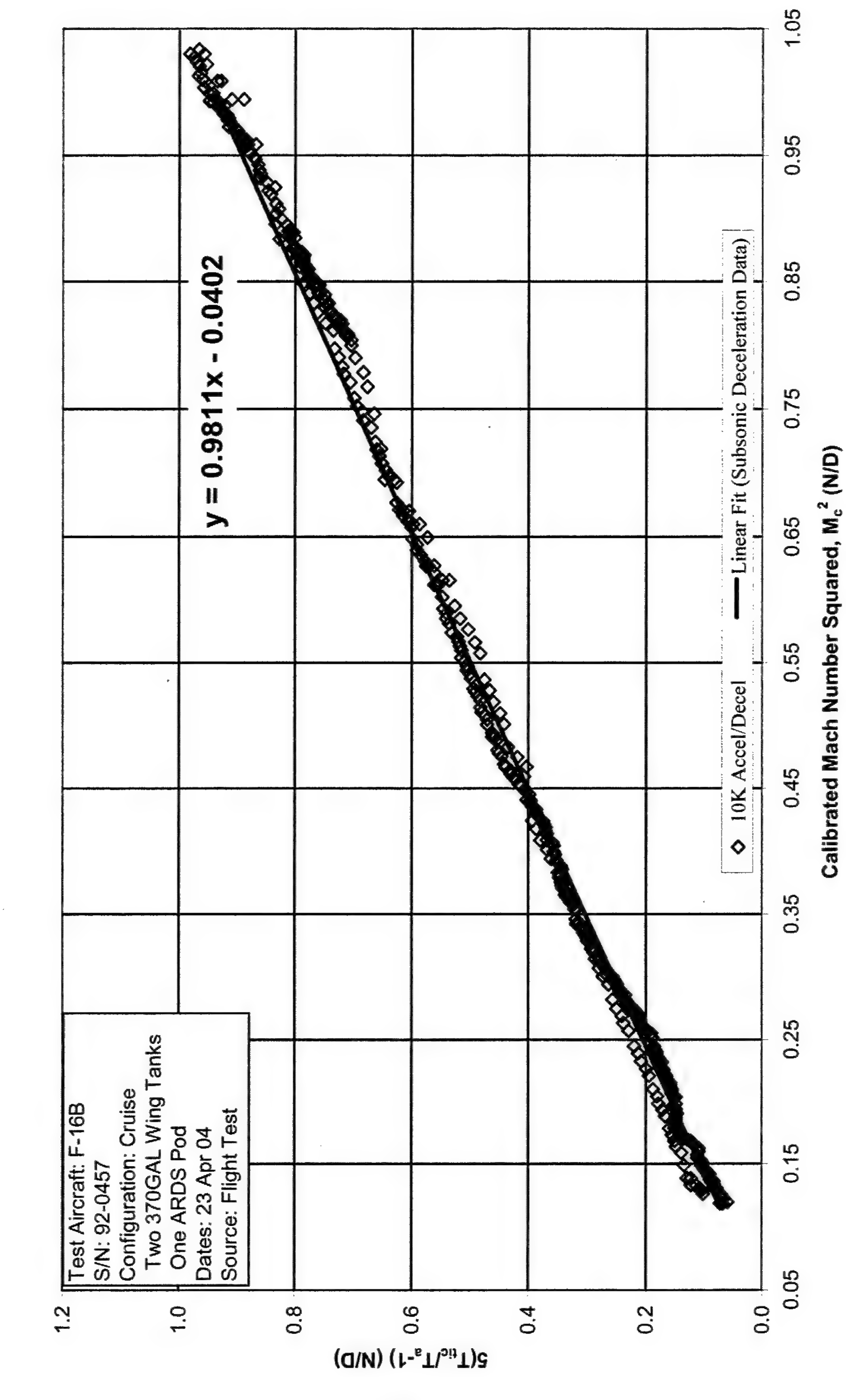


Figure 63. Total Air Temperature Probe Recovery Factor (20,000 ft PA Level Accel/Decel)

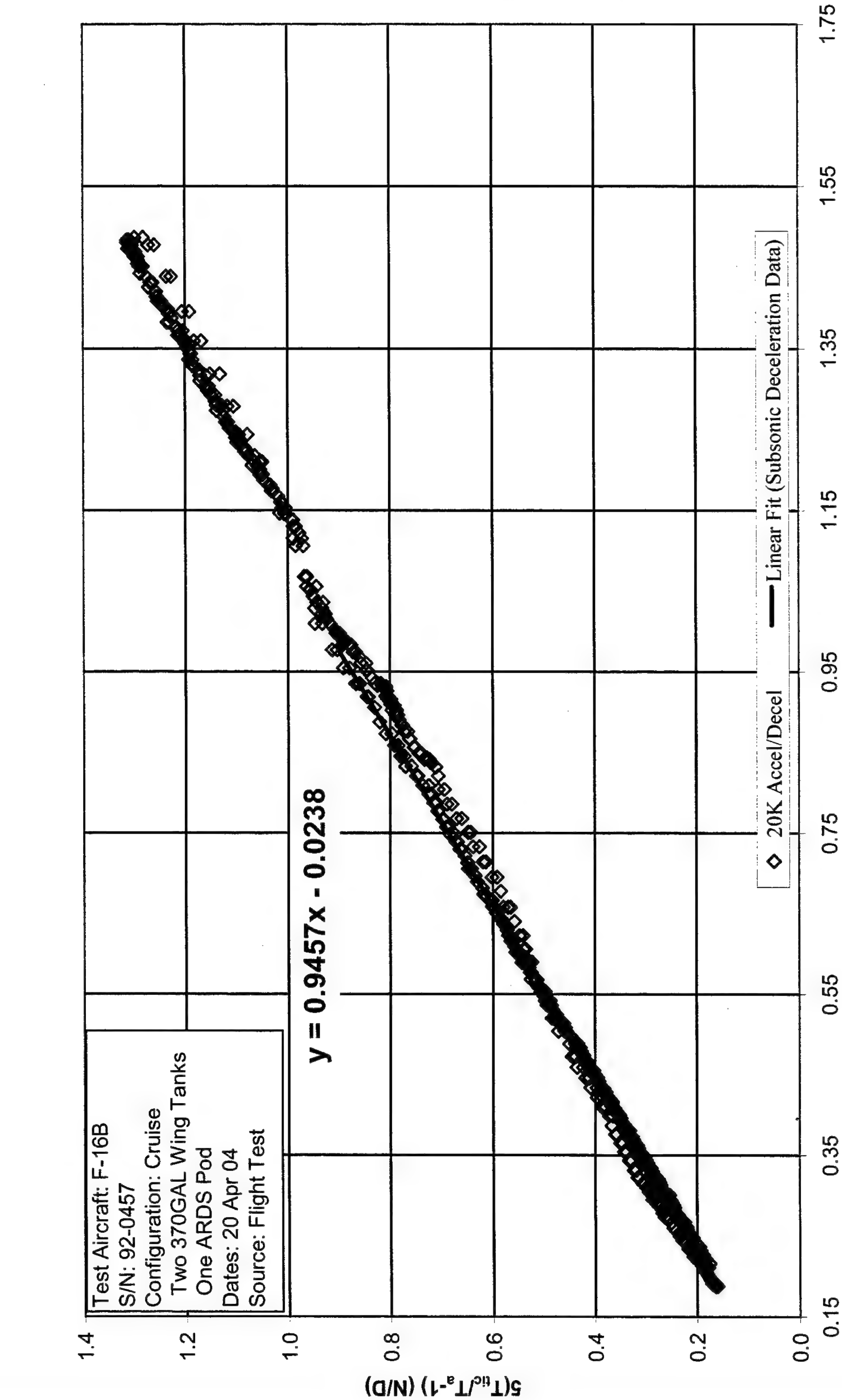


Figure 64. Total Air Temperature Probe Recovery Factor (30,000 ft PA Level Accel/Decel)

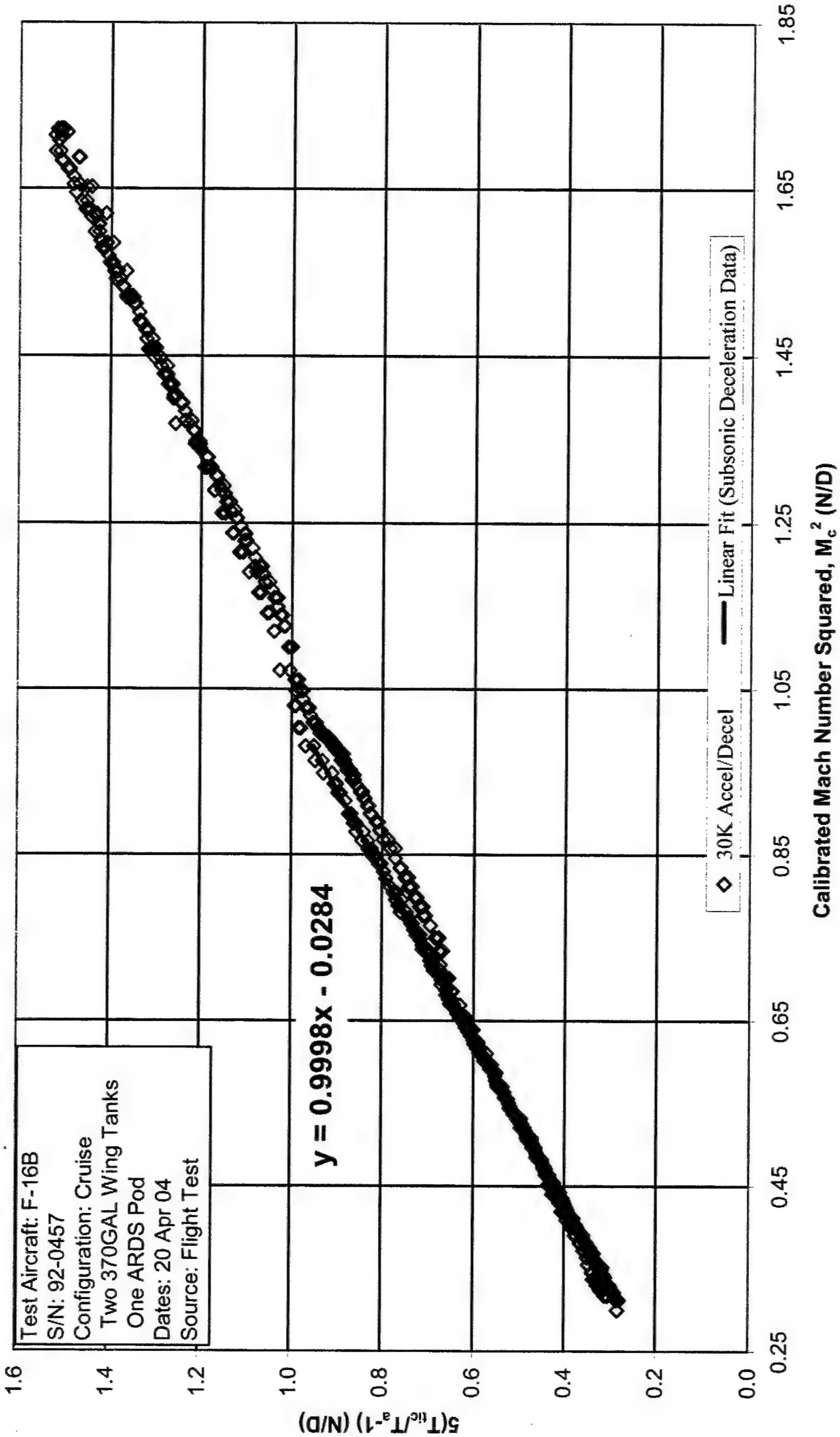


Figure 65. Total Air Temperature Probe Recovery Factor (35,000 ft PA Level Accel/Decel)

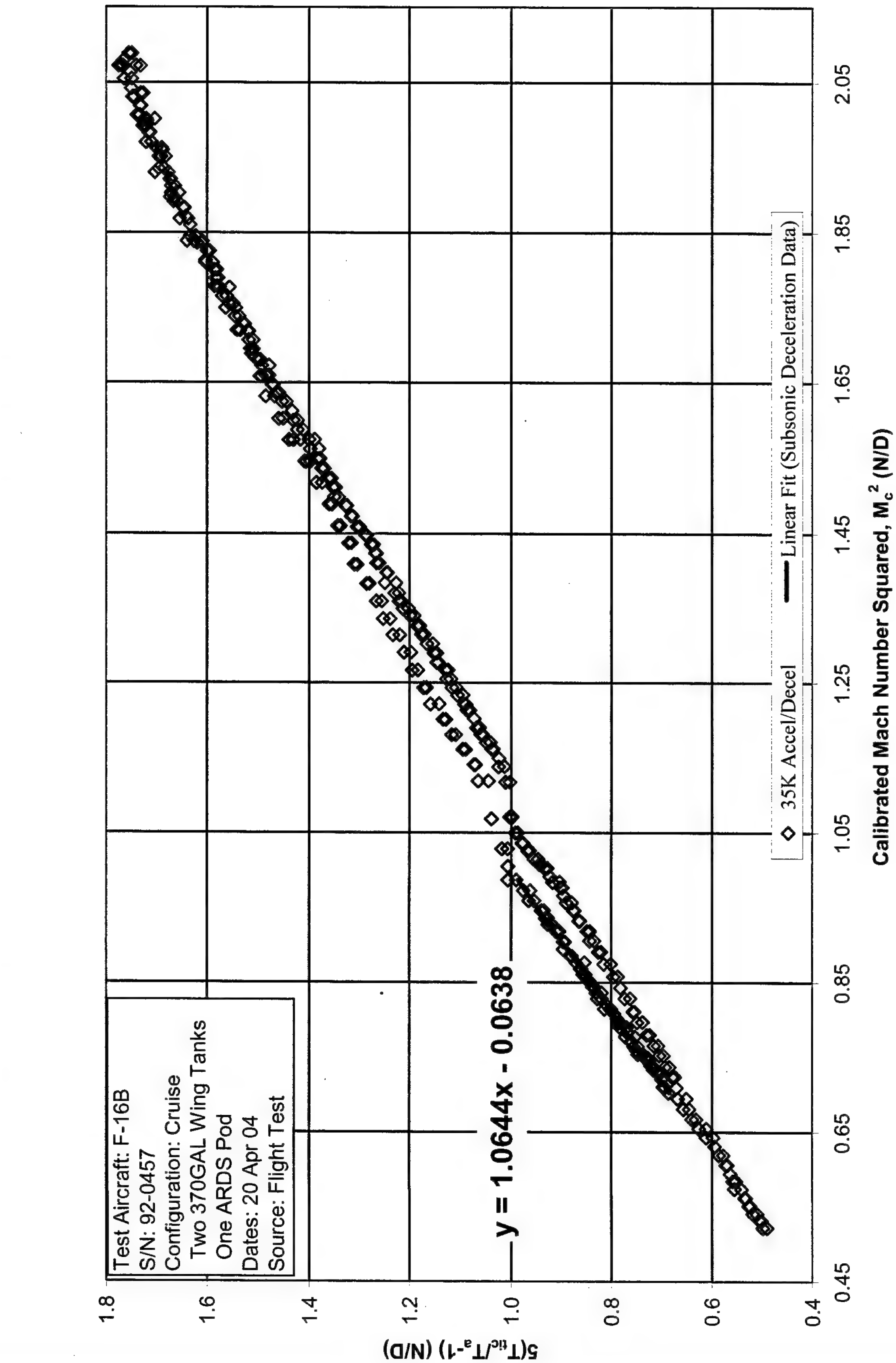
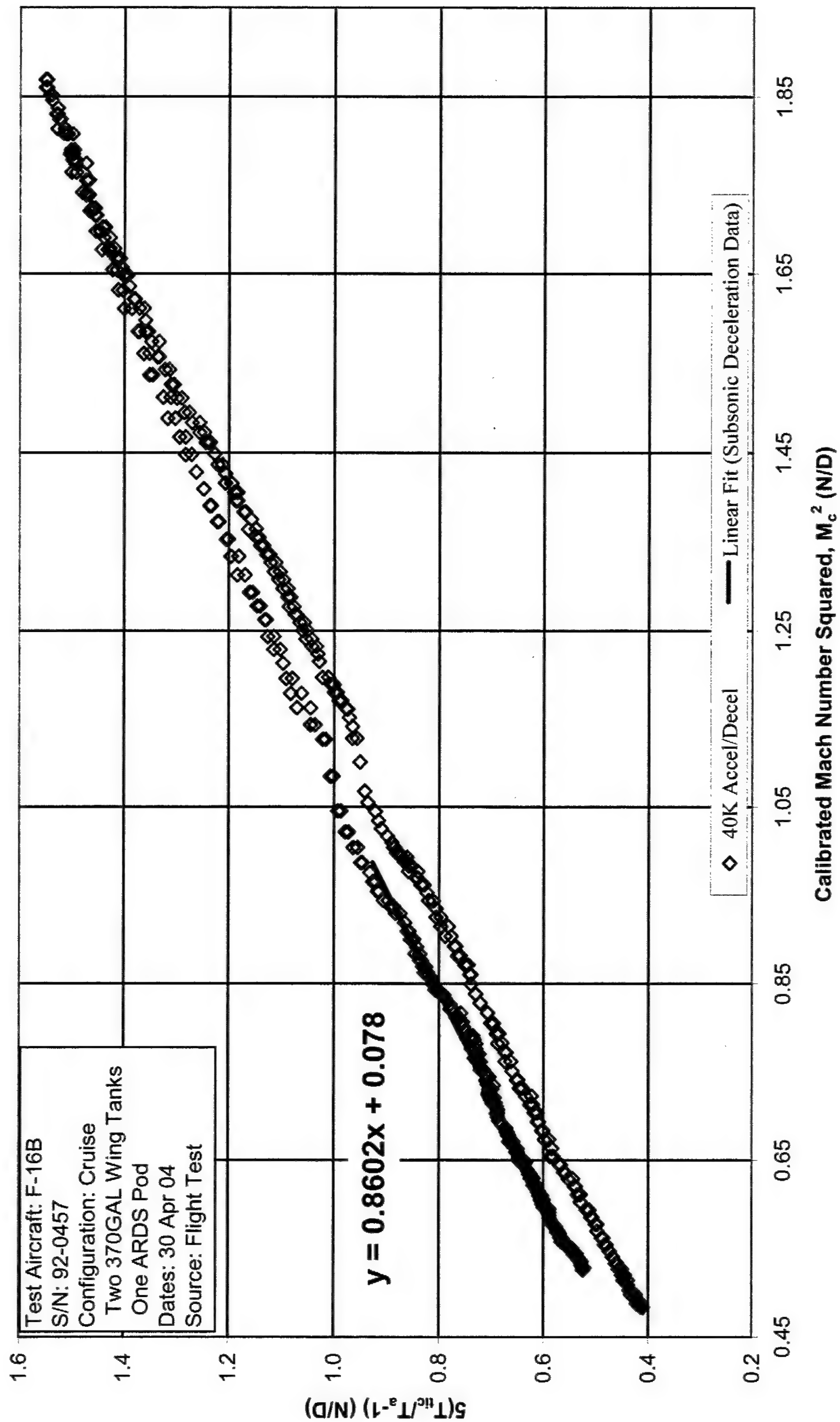


Figure 66. Total Air Temperature Probe Recovery Factor (40,000 ft PA Level Accel/Decel)



APPENDIX B – LESSONS LEARNED

Human Factors

F-16B S/N 92 0457 had several special controls and displays installed in the rear cockpit (RCP) for interfacing with the pacer instrumentation and data acquisition system. The controls included an event mark button, a display configuration selector, and DAS recorder controls on the left console, aft of the time display, Figure 67. Both the MARS II tape and the PCMCIA DAS recorders had power and record/stop toggle switches. Additionally, the PCMCIA recorder had high and low data rate recording options. All controls were clearly labeled. The event button was in an awkward location that induced operator arm fatigue and interfered with throttle operation. It was easy to bump the throttle during low power settings when operating the event button or any other pacer system controls. Due to this, it was best to hold one's finger on the event button throughout all maneuvers. This awkward position led to muscle fatigue in the left arm. Place an event button on the RCP instrument panel in an easily accessible location.

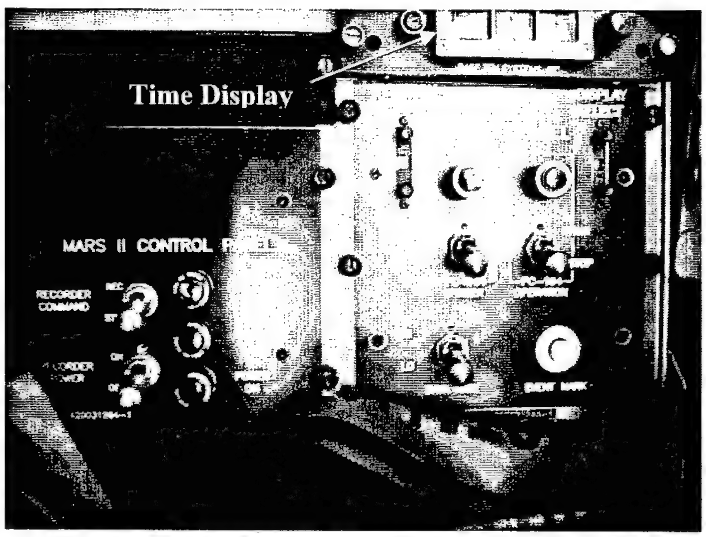


Figure 67. Rear Cockpit Pacer Controls And Time Display

The displays included GPS time on the left console, Figure 67, and a multi-window LCD display of altitude, airspeed, and event correlation number on the left side of the instrument panel, Figure 68. Recording handheld data required looking down to read the time, and then looking up to read the other displays. This required significant FTE workload during elevated load factor test points. Additionally, at near idle power settings, the throttle blocked viewing the time display. Move the time display so that it is not blocked from view during flight and is within view of the altitude, airspeed, and correlation number displays. The multi-display was not externally labeled, but once power was applied "Hc", "Vc", and "CN" appeared on the LCDs. However, adding external labels would improve usability. Add labels to the altitude, airspeed, and correlation number displays.

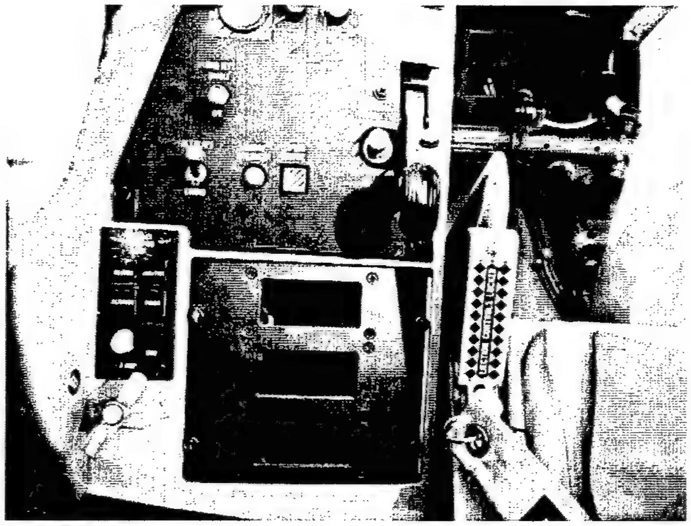


Figure 68. Rear Cockpit Data Display

An event was actuated by holding the event button down for approximately 1 second. This was an excessive time delay between the event button actuation and the actual event being recorded in the DAS. Remove the time delay so that the computer events the data immediately upon event button actuation. After event actuation, the altitude, airspeed, and correlation number displays froze for approximately 10 seconds to allow for hand recording of the data, which was a good feature of the system. Overall, the human factors design of the pacer system was marginal, and should be corrected prior to use as a developmental test pacer aircraft.

APPENDIX C – INSTRUMENTATION LIST

Flyby Tower Instrumentation		
Item	**Part Number**	**Serial Number**
Setra Digital Pressure Gauge	370	2017712
Omega Digital Thermometer	HH-41	305107

Aircraft Instrumentation			
Item	**Part Number**	**Serial Number**	**Description**
TTU-205F		1256	
Dual Sonic Encoder	PS7000	0011	Aircraft System 1 pressure transducer
Dual Sonic Encoder	PS7000	0014	Aircraft System 2 pressure transducer

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APPENDIX D – END-TO-END GROUND TEST RESULTS

		19 Feb 04 Calibration		28 Feb 04 Spot Check	
Test Set Readings		Pacer Display Readings		Pacer Display Readings	
Hp (ft)	Airspeed (KCAS)	Pressure Altitude (h_c)	Calibrated Airspeed (V_c)	Pressure Altitude (h_c)	Calibrated Airspeed (V_c)
5000	150	5008	150.34		
5000	180	5029	181.31		
5000	250	5063	252.13		
5000	300	5087	302.41	5090	302.53
5000	350	5114	352.67		
5000	400	5140	402.70	5141	402.73
5000	450	5158	452.57		
5000	500	5162	502.28	5163	502.40
5000	550	5177	552.15		
5000	650	4711	647.21		
5000	750	4489	749.38		
20000	180	20048	181.66		
20000	250	20089	252.08	20093	252.22
20000	300	20119	302.23	20122	302.49
20000	350	20137	352.11	20141	352.23
20000	375	20140	376.96		
20000	400	20143	401.82	20148	401.90
20000	425	20155	426.82	20159	426.78
20000	450	20505	455.30	20508	455.27
20000	550	19367	546.12		
20000	650	19617	659.69		
40000	180	40079	181.75		
40000	200	40094	201.82	40102	202.11
40000	225	40106	226.70		
40000	250	40107	251.53	40118	251.98
40000	275	40118	276.45		
40000	300	40681	305.89	40702	306.23
40000	350	39335	345.87		
40000	400	39591	401.12		
35000	250	35111	251.83		
30000	250	30105	252.03		
25000	250	25094	252.05		
15000	250	15076	252.23		
10000	250	10067	252.33		

Table 5. End-to-End Ground Test Results

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APPENDIX E – RAW DATA

Table 6. Tower Fly-by Aircraft Raw Data

Date	Time (L)	Target A/S (knots)	Grid Reading (N/D)	P_{sic} (in Hg)	P_{tic} (in Hg)	T_{tic} (deg. K)	Angle of Attack
4/7/2004	7:37:35	300	2.8	27.575	31.997	293.0	4.8
4/7/2004	7:42:10	325	3.5	27.570	32.982	295.9	4.2
4/7/2004	7:46:12	350	3.3	27.578	33.410	297.1	3.7
4/7/2004	7:50:00	375	3.1	27.597	34.980	301.2	2.9
4/7/2004	7:53:37	400	3	27.613	35.584	302.9	2.7
4/7/2004	7:57:12	425	2.2	27.647	36.853	305.6	2.4
4/7/2004	8:00:42	450	2.6	27.644	38.296	308.2	2.0
4/7/2004	8:04:43	500	3	27.629	41.582	315.4	1.5
4/7/2004	8:08:32	525	3.1	27.628	42.096	316.6	1.4
4/7/2004	8:12:28	550	2.5	27.636	45.051	322.6	1.2
4/7/2004	8:16:15	575	2	27.655	45.575	324.0	1.1
4/7/2004	8:20:47	275	2.5	27.581	31.096	293.3	5.2
4/7/2004	8:25:36	250	2.1	27.582	30.521	291.9	6.3
4/7/2004	8:30:12	200	2.9	27.539	29.410	288.9	9.4
4/7/2004	8:34:54	180	3.4	27.516	29.011	288.3	11.6
4/7/2004	8:39:39	190	3.5	27.524	29.183	288.8	10.7
4/7/2004	8:44:23	225	2.7	27.566	30.160	291.8	6.7
4/7/2004	8:48:36	325	2.6	27.604	33.009	299.1	3.1
4/7/2004	8:52:43	475	2.3	27.658	39.811	314.3	1.5
4/12/2004	7:34:13	300	1.4	27.679	32.179	293.4	5.3
4/12/2004	7:38:13	325	1.3	27.689	33.022	295.6	3.8
4/12/2004	7:41:59	350	1.6	27.689	33.870	298.1	3.5
4/12/2004	7:45:31	375	1.2	27.707	34.851	300.6	2.9
4/12/2004	7:48:55	400	1.9	27.702	35.888	303.1	2.5
4/12/2004	7:52:19	425	1.7	27.709	37.185	305.2	2.1
4/12/2004	7:55:32	450	2.2	27.703	38.238	308.7	1.8
4/12/2004	7:58:40	475	2	27.715	39.780	311.6	1.5
4/12/2004	8:01:45	500	2.2	27.713	41.194	314.1	1.4
4/12/2004	8:04:49	525	2.2	27.703	42.822	317.4	1.2
4/12/2004	8:08:02	550	2.1	27.705	44.512	320.6	1.0
4/12/2004	8:11:13	575	2.1	27.705	46.617	324.7	1.0
4/12/2004	8:15:09	275	1.4	27.669	31.424	292.6	4.7
4/12/2004	8:19:11	250	2.1	27.641	30.765	290.9	5.6
4/12/2004	8:23:19	225	1.7	27.641	30.140	289.4	6.9
4/12/2004	8:27:41	200	2.3	27.621	29.574	288.4	8.3
4/12/2004	8:32:30	190	1.9	27.624	29.371	287.8	9.3
4/12/2004	8:37:14	180	1.9	27.621	29.197	287.4	9.7
4/12/2004	8:41:25	300	1.4	27.687	32.207	295.6	3.5
4/12/2004	8:45:17	180	1.7	27.631	29.189	287.8	9.6

Date	Time (L)	Target A/S (knots)	Grid Reading (N/D)	P_{sic} (in Hg)	P_{tic} (in Hg)	T_{tic} (deg. K)	Angle of Attack
4/12/2004	8:51:24	170	2.2	27.613	29.050	287.8	10.1
4/13/2004	7:31:12	300	2.2	27.625	32.299	297.1	4.7
4/13/2004	7:35:08	325	2.3	27.634	33.175	299.5	3.8
4/13/2004	7:38:46	350	2.2	27.653	34.518	303.2	3.1
4/13/2004	7:42:20	375	2.4	27.653	35.093	304.4	2.7
4/13/2004	7:45:42	400	2.1	27.672	36.524	307.3	2.4
4/13/2004	7:48:54	425	2	27.681	37.218	309.2	2.1
4/13/2004	7:52:21	450	2.5	27.674	37.977	310.9	2.0
4/13/2004	7:55:35	475	2.4	27.677	39.498	314.4	1.7
4/13/2004	7:58:54	500	2.6	27.676	41.346	318.0	1.3
4/13/2004	8:02:26	525	2.2	27.682	42.936	321.5	1.2
4/13/2004	8:05:56	550	2.4	27.672	44.765	325.7	1.1
4/13/2004	8:09:25	575	1.9	27.685	46.848	330.1	1.0
4/13/2004	8:13:24	275	2.1	27.621	31.392	296.2	4.6
4/13/2004	8:17:30	250	1.8	27.618	30.689	294.5	5.6
4/13/2004	8:21:41	225	2.5	27.595	30.079	293.0	7.0
4/13/2004	8:26:18	200	2.2	27.596	29.575	291.8	8.8
4/13/2004	8:31:13	180	2.2	27.585	29.210	290.9	10.0
4/13/2004	8:36:04	190	2.5	27.585	29.368	291.5	9.2
4/13/2004	8:40:17	300	2.5	27.628	32.131	299.1	3.5
4/13/2004	8:44:14	325	2.2	27.645	33.072	301.8	2.9
4/13/2004	8:47:12	275	2.1	27.626	31.431	297.4	4.2
4/13/2004	8:53:07	170	3	27.558	29.024	291.1	10.7
4/13/2004	8:56:38	450	2.4	27.684	38.557	314.6	1.2
4/30/2004	7:22:18	300	2	27.707	32.467	295.1	4.5
4/30/2004	7:25:44	500	3	27.725	41.415	315.3	1.5
4/30/2004	7:30:04	200	2	27.669	29.749	288.0	9.6

Table 7. Fly-By Tower Raw Data (7 April 2004)

Time	Setra (in Hg)	Setra (ft)	Correction (ft)[1]	Zero Grid Alt (ft)	T_a (°F)
6:59:00	27.5801	2237	-3	2234	46.1
7:04:00	27.5819	2236	-3	2233	46.3
7:09:00	27.5819	2236	-3	2233	46.6
7:14:00	27.5845	2233	-3	2230	46.9
7:19:00	27.5828	2235	-3	2232	47.4
7:24:00	27.586	2231	-3	2228	48.0
7:29:00	27.5872	2230	-3	2227	48.5
7:34:00	27.5878	2230	-3	2227	48.9
7:39:00	27.5872	2230	-3	2227	49.3
7:44:00	27.5878	2230	-3	2227	49.8
7:49:00	27.5887	2229	-3	2226	50.3
7:54:00	27.591	2227	-3	2224	50.7
7:59:00	27.5913	2226	-3	2223	51.3
8:04:00	27.5922	2225	-3	2222	51.9
8:09:00	27.5928	2225	-3	2222	52.3
8:14:00	27.594	2224	-3	2221	53.0
8:19:00	27.5952	2222	-3	2219	54.0
8:24:00	27.5949	2223	-3	2220	54.4
8:29:00	27.5952	2222	-3	2219	55.2
8:34:00	27.5963	2221	-3	2218	55.9
8:39:00	27.5969	2221	-3	2218	56.3
8:44:00	27.596	2222	-3	2219	56.7
8:49:00	27.596	2222	-3	2219	57.3
8:54:00	27.5946	2223	-3	2220	58.2
8:59:00	27.5931	2224	-3	2221	59.0
9:04:00	27.5922	2225	-3	2222	60.2
9:09:00	27.5919	2226	-3	2223	60.4
9:14:00	27.5934	2224	-3	2221	61.0
9:19:00	27.5931	2224	-3	2221	62.0
9:24:00	27.5925	2225	-3	2222	62.2

[1] The Setra pressure transducer was recalibrated after the test flights and found to have a 3 ft error.

Table 8. Fly-By Tower Raw Data (12 April 2004)

Time	Setra (in Hg)	Setra (ft)	Correction (ft)[1]	Zero Grid Alt (ft)	T_a (°F)
7:00:30	27.635	2183	-3	2180	47.3
7:05:30	27.6356	2183	-3	2180	47.0
7:10:30	27.6374	2181	-3	2178	46.8
7:15:30	27.6383	2180	-3	2177	47.0
7:20:30	27.64	2178	-3	2175	47.4
7:25:30	27.6397	2178	-3	2175	48.1
7:30:30	27.6412	2177	-3	2174	48.6
7:35:30	27.6433	2175	-3	2172	49.0
7:40:30	27.6445	2174	-3	2171	49.9
7:45:30	27.6442	2174	-3	2171	50.3
7:50:30	27.6454	2173	-3	2170	50.1
7:55:30	27.646	2172	-3	2169	50.3
8:00:30	27.6468	2171	-3	2168	50.5
8:05:30	27.6495	2169	-3	2166	51.1
8:10:30	27.6506	2168	-3	2165	51.3
8:15:30	27.6504	2168	-3	2165	51.6
8:20:30	27.6504	2168	-3	2165	52.2
8:25:30	27.6516	2167	-3	2164	52.7
8:30:30	27.6522	2166	-3	2163	53.6
8:35:30	27.6533	2165	-3	2162	54.1
8:40:30	27.6545	2164	-3	2161	54.3
8:45:30	27.6539	2164	-3	2161	55.0
8:50:30	27.6539	2164	-3	2161	55.0
8:55:30	27.6545	2164	-3	2161	55.6
9:00:30	27.6533	2165	-3	2162	56.4
9:05:30	27.6533	2165	-3	2162	57.1
9:10:30	27.6533	2165	-3	2162	57.3
9:15:30	27.6542	2164	-3	2161	59.3
9:20:30	27.656	2162	-3	2159	60.0

[1] The Setra pressure transducer was recalibrated after the test flights and found to have a 3 ft error.

Table 9. Fly-By Tower Raw Data (13 April 2004)

Time	Setra (in Hg)	Setra (ft)	Correction (ft)[1]	Zero Grid Alt (ft)	T_a (°F)
6:55:00	27.6105	2207	-3	2204	51.6
7:00:00	27.6102	2208	-3	2205	52.6
7:05:00	27.6105	2207	-3	2204	51.9
7:10:00	27.6126	2205	-3	2202	51.6
7:15:00	27.6126	2205	-3	2202	52.5
7:20:00	27.6126	2205	-3	2202	53.4
7:25:00	27.6144	2203	-3	2200	53.1
7:30:00	27.6161	2202	-3	2199	53.1
7:35:10	27.6188	2199	-3	2196	53.8
7:40:00	27.6214	2197	-3	2194	54.5
7:45:00	27.6235	2194	-3	2191	55.2
7:50:00	27.6235	2194	-3	2191	55.9
7:55:00	27.6235	2194	-3	2191	56.7
8:00:00	27.6232	2195	-3	2192	57.4
8:05:00	27.6214	2197	-3	2194	57.9
8:10:00	27.6217	2196	-3	2193	58.5
8:15:10	27.6211	2197	-3	2194	58.5
8:20:00	27.6214	2197	-3	2194	58.7
8:25:00	27.6223	2196	-3	2193	59.0
8:30:00	27.6235	2194	-3	2191	59.4
8:35:00	27.6241	2194	-3	2191	59.1
8:40:00	27.6241	2194	-3	2191	59.5
8:45:00	27.6226	2195	-3	2192	60.8
8:50:00	27.6229	2195	-3	2192	60.7
8:55:00	27.6235	2194	-3	2191	61.7
9:00:00	27.6232	2195	-3	2192	62.2
9:05:00	27.6229	2195	-3	2192	62.2
9:10:00	27.6217	2196	-3	2193	62.8
9:15:00	27.6203	2198	-3	2195	63.3
9:20:00	27.6206	2197	-3	2194	63.8
9:25:00	27.6214	2197	-3	2194	63.6
9:30:00	27.6223	2196	-3	2193	64.4

[1] The Setra pressure transducer was recalibrated after the test flights and found to have a 3 ft error.

Table 10. Fly-By Tower Raw Data (30 April 2004)

Time	Setra (in Hg)	Setra (ft)	Correction (ft)[1]	Zero Grid Alt (ft)	T_a (°F)
6:30:00	27.6713	2147	-3	2144	49.0
6:35:00	27.6734	2145	-3	2142	49.9
6:40:00	27.6752	2143	-3	2140	50.6
6:46:00	27.6773	2141	-3	2138	50.7
6:50:00	27.6796	2139	-3	2136	50.8
6:55:00	27.6835	2135	-3	2132	50.8
7:00:00	27.6846	2134	-3	2131	51.2
7:05:00	27.687	2132	-3	2129	51.6
7:10:00	27.6882	2131	-3	2128	51.2
7:15:00	27.6908	2128	-3	2125	51.2
7:20:00	27.6923	2127	-3	2124	50.3
7:25:00	27.6944	2125	-3	2122	47.8
7:30:00	27.6967	2122	-3	2119	48.5
7:35:00	27.697	2122	-3	2119	49.5
7:40:00	27.697	2122	-3	2119	50.9
7:45:00	27.6994	2120	-3	2117	52.4
7:50:00	27.7029	2116	-3	2113	52.8
7:55:00	27.7044	2115	-3	2112	52.9
8:00:00	27.7041	2115	-3	2112	53.8

[1] The Setra pressure transducer was recalibrated after the test flights and found to have a 3 ft error.

Table 11. Pace Raw Data

Time (Z)	Alt (ft)	Target Mach (N/D)	F-15 H_c (feet)	F-15 V_c (KCAS)	F-15 T_a (Deg K)	F-15 M_c (N/D)	F-16 P_{sic} (in Hg)	F-16 P_{tic} (in Hg)	F-16 T_{tic} (deg. K)	F-16 Angle of Attack
22:15:10	10K	0.35	9,958	198.7	276.2	0.360	20.646	22.544	282.6	9.5
22:14:31	10K	0.4	9,975	220.6	276.7	0.400	20.633	23.031	284.9	7.6
22:13:36	10K	0.45	10,002	250.7	276.8	0.450	20.622	23.639	287.0	6.0
21:04:37	10K	0.5	9,918	276.3	275.6	0.500	20.728	24.426	288.4	5.9
21:05:34	10K	0.55	9,939	305.7	275.9	0.550	20.699	25.349	291.6	4.4
22:16:09	10K	300	9,941	301.3	276.4	0.540	20.679	25.215	291.6	4.0
21:06:33	10K	0.6	9,957	333.5	276.2	0.600	20.690	26.194	294.9	3.8
21:07:42	10K	0.65	9,940	361.5	276.8	0.650	20.704	27.280	298.5	3.1
21:08:30	10K	0.7	9,926	389.8	276.6	0.700	20.724	28.608	302.0	2.5
21:09:21	10K	0.75	9,891	421.8	278.0	0.750	20.738	29.943	304.8	2.1
21:11:43	10K	0.8	9,902	449.3	278.7	0.800	20.721	31.543	309.0	1.7
21:12:25	10K	0.85	9,897	474.9	278.1	0.840	20.721	32.996	312.1	1.5
21:13:34	10K	0.9	9,799	505.6	277.3	0.890	20.795	34.694	316.5	1.2
21:14:16	10K	0.92	9,761	518.3	276.9	0.910	20.824	35.640	318.7	1.4
22:19:00	10K	0.93	9,776	523.1	276.5	0.920	20.800	36.803	319.9	1.4
22:18:15	10K	0.94	9,881	528.7	276.3	0.930	20.848	36.218	320.1	1.2
22:18:40	10K	0.95	9,843	534.0	276.4	0.940	20.764	36.507	320.4	1.3
22:10:27	20K	0.45	20,018	207.3	253.7	0.460	13.782	15.809	263.7	8.4
21:17:13	20K	0.5	19,998	230.6	254.1	0.510	13.789	16.397	266.7	7.6
21:17:58	20K	0.55	19,967	251.8	254.7	0.550	13.805	16.920	269.6	6.4
21:18:48	20K	0.6	19,955	276.9	254.2	0.600	13.809	17.596	271.8	4.9
21:19:33	20K	0.65	19,941	300.5	254.2	0.650	13.822	18.299	274.6	4.4
22:08:54	20K	300	20,054	300.4	253.9	0.650	13.777	18.235	274.3	3.8
21:20:13	20K	0.7	19,934	322.3	254.0	0.700	13.824	19.102	277.5	3.7
21:22:09	20K	0.75	19,990	347.8	253.7	0.750	13.813	19.882	280.8	3.1
21:22:53	20K	0.8	19,952	371.3	254.8	0.800	13.831	20.846	283.9	2.4
21:23:33	20K	0.85	19,907	398.5	254.9	0.850	13.860	22.086	287.9	2.1
21:24:17	20K	0.9	19,860	423.4	254.4	0.900	13.878	23.275	291.8	1.8
21:24:51	20K	0.92	19,806	433.1	254.6	0.920	13.908	23.751	293.4	1.7
21:25:22	20K	0.93	19,778	439.1	254.8	0.930	13.935	24.134	294.9	1.8
21:25:47	20K	0.94	19,712	444.0	255.0	0.930	13.978	24.418	295.7	1.8
21:26:16	20K	0.95	19,694	449.4	254.8	0.940	13.991	24.723	296.6	1.7
21:28:58	30K	0.55	29,871	205.1	229.0	0.550	8.979	11.229	243.9	8.3
21:29:47	30K	0.6	29,893	223.9	228.8	0.600	8.969	11.469	244.9	7.6
21:32:24	30K	0.65	29,929	243.6	228.8	0.650	8.954	11.922	247.6	6.5
21:33:24	30K	0.7	29,961	261.5	228.6	0.700	8.934	12.239	249.2	5.5
21:34:10	30K	0.75	29,957	284.4	228.9	0.750	8.938	12.986	253.6	4.4
22:06:39	30K	300	29,932	302.2	228.4	0.790	8.946	13.484	255.7	3.5
21:34:48	30K	0.8	29,950	303.6	228.7	0.800	8.940	13.551	256.9	3.8
21:35:30	30K	0.85	29,920	325.6	228.6	0.850	8.943	14.340	260.1	3.2

Time (Z)	Alt (ft)	Target Mach (N/D)	F-15 H_c (feet)	F-15 V_c (KCAS)	F-15 T_a (Deg K)	F-15 M_c (N/D)	F-16 P_{sic} (in Hg)	F-16 P_{tic} (in Hg)	F-16 T_{tic} (deg. K)	F-16 Angle of Attack
21:36:07	30K	0.9	29,905	346.6	228.6	0.900	8.947	15.034	263.1	2.7
21:36:30	30K	0.92	29,869	354.8	228.8	0.920	8.959	15.428	264.5	2.5
21:36:51	30K	0.93	29,839	359.7	228.9	0.930	8.972	15.655	266.0	2.4
21:37:15	30K	0.94	29,811	364.1	228.9	0.940	8.994	15.729	266.3	2.6
21:37:36	30K	0.95	29,771	367.7	229.0	0.950	9.012	15.939	267.3	2.5
21:40:33	35K	0.6	34,951	200.9	215.8	0.600	7.093	9.042	230.0	9.6
21:42:15	35K	0.65	34,920	218.3	216.1	0.650	7.100	9.438	232.7	7.9
21:45:36	35K	0.7	34,925	234.1	215.7	0.700	7.103	9.853	235.3	6.6
21:46:39	35K	0.75	34,986	252.4	215.4	0.750	7.075	10.279	238.3	5.2
21:47:28	35K	0.8	35,023	271.0	214.8	0.800	7.058	10.695	240.5	4.8
21:48:17	35K	0.85	35,037	291.7	214.4	0.850	7.048	11.366	244.3	3.8
22:04:48	35K	300	34,956	298.2	215.7	0.870	7.076	11.533	246.1	3.6
21:48:58	35K	0.9	35,005	311.4	214.6	0.900	7.049	11.990	247.6	3.0
21:49:28	35K	0.92	34,974	317.8	214.7	0.920	7.063	12.144	248.5	3.1
21:49:48	35K	0.93	34,933	322.7	214.9	0.930	7.076	12.349	249.8	3.0
21:50:08	35K	0.94	34,900	326.5	215.2	0.940	7.092	12.508	250.8	3.0
21:50:26	35K	0.95	34,867	330.2	215.1	0.950	7.115	12.612	251.1	3.2
21:55:04	40K	0.7	39,944	214.9	209.5	0.710	5.568	7.562	227.3	9.0
21:55:51	40K	0.75	39,854	228.2	210.0	0.750	5.602	8.145	231.9	6.7
21:56:51	40K	0.8	39,818	245.0	209.4	0.800	5.610	8.547	234.0	5.6
21:57:49	40K	0.85	39,873	261.9	208.7	0.850	5.584	8.987	236.8	4.8
21:58:45	40K	0.9	39,914	279.0	208.4	0.900	5.567	9.449	240.3	4.0
21:59:19	40K	0.92	39,894	285.7	208.4	0.920	5.570	9.654	241.7	3.6
21:59:53	40K	0.93	39,864	289.2	208.3	0.930	5.578	9.725	242.3	3.4
22:01:18	40K	0.94	40,106	290.8	208.2	0.940	5.515	9.750	243.1	3.6
22:01:40	40K	0.95	40,094	295.4	208.2	0.950	5.528	9.807	243.4	3.8

LIST OF ABBREVIATIONS

Abbreviation	Definition
AATIS	Advanced Airborne Test Instrumentation System
AFFTC	Air Force Flight Test Center
AFMC	Air Force Material Command
AGL	Above Ground Level
AoA	Angle of Attack
ARDS	Advanced Range Data System
FTT	Flight Test Technique
GPS	Global Positioning System
HUD	Heads Up Display
JON	Job Order Number
KCAS	Knots Calibrated Airspeed
KIAS	Knots Indicated Airspeed
LCD	Liquid Crystal Display
M	Mach Number
MSL	Mean Sea Level
MOP	Measure of Performance
N/D	Non-Dimensional
OPSEC	Operations Security
PA	Pressure Altitude
PC	Personal Computer
PCM	Pulse Code Modulation
PCMCIA	Personal Computer Memory Card International
RCP	Rear Cockpit
S/N	Serial Number
TFB	Tower Fly-by
TMP	Test Management Project
TPS	Test Pilot School

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